EDN

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Issue 17

CONDITIONING TECHNIQUES FOR REAL-WORLD SENSORS

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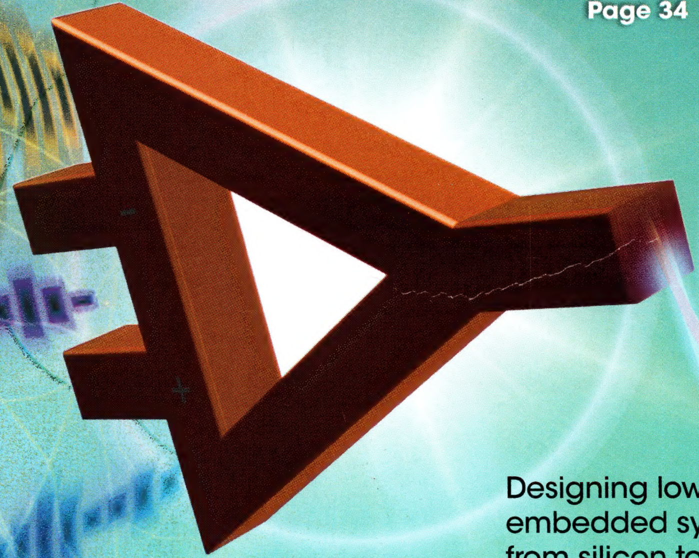

Designing low-energy embedded systems from silicon to software
Page 27

Add LED intelligence to improve light quality, efficiency, and cost
Page 49

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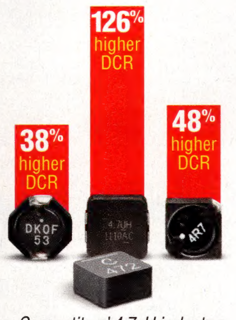

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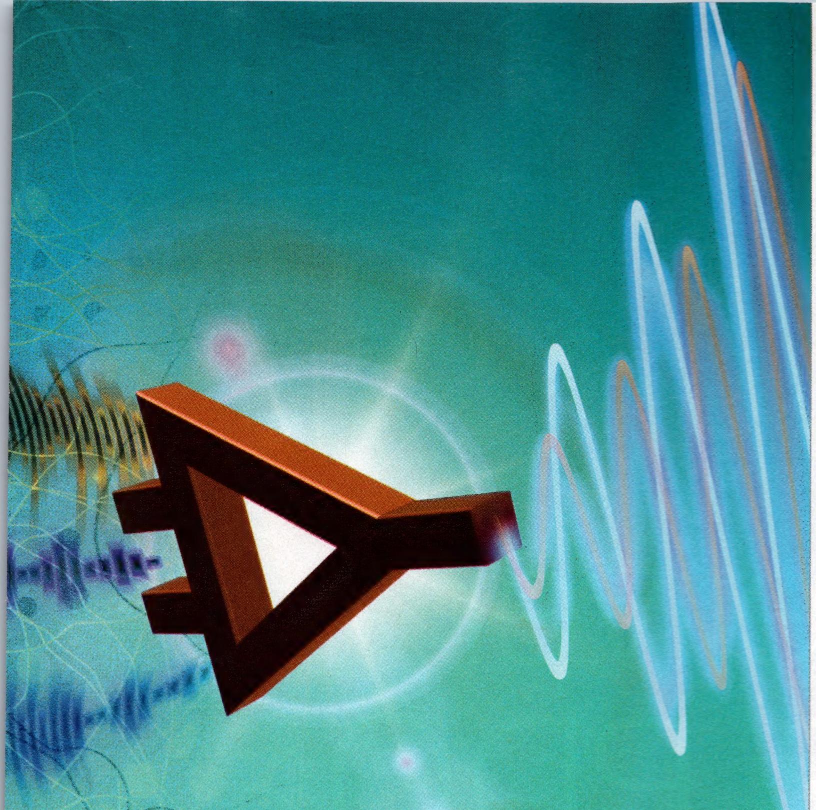
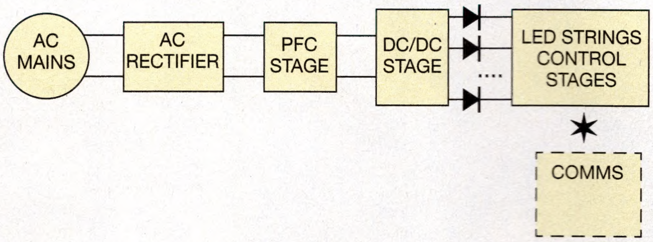
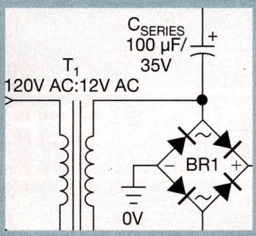
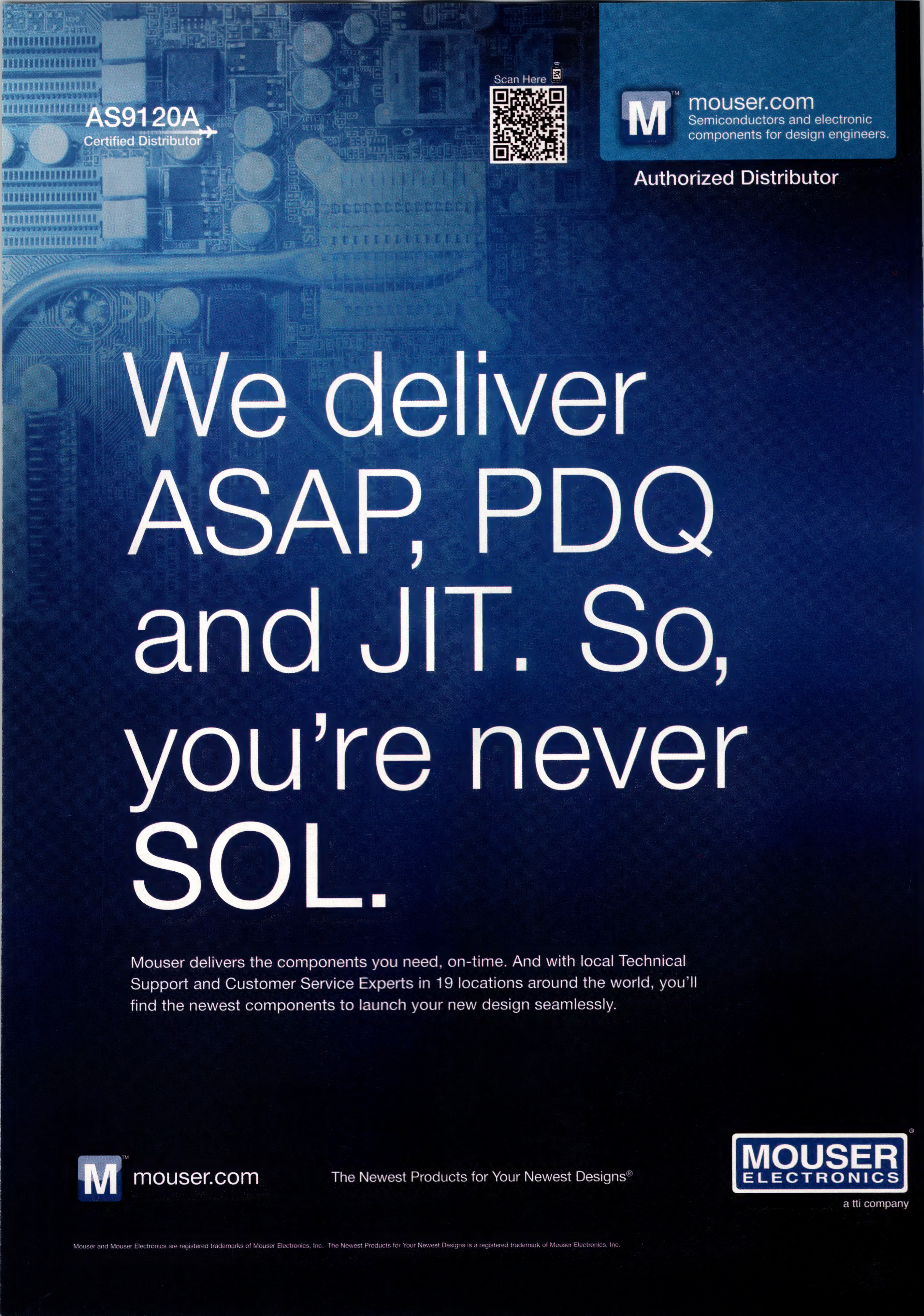




DESIGNIDEAS



▶ Submit your own Design Idea to edndesignideas@ubm.com.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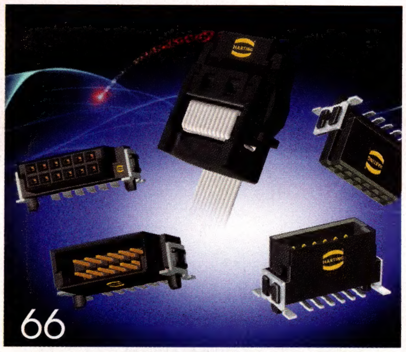
DEPARTMENTS & COLUMNS



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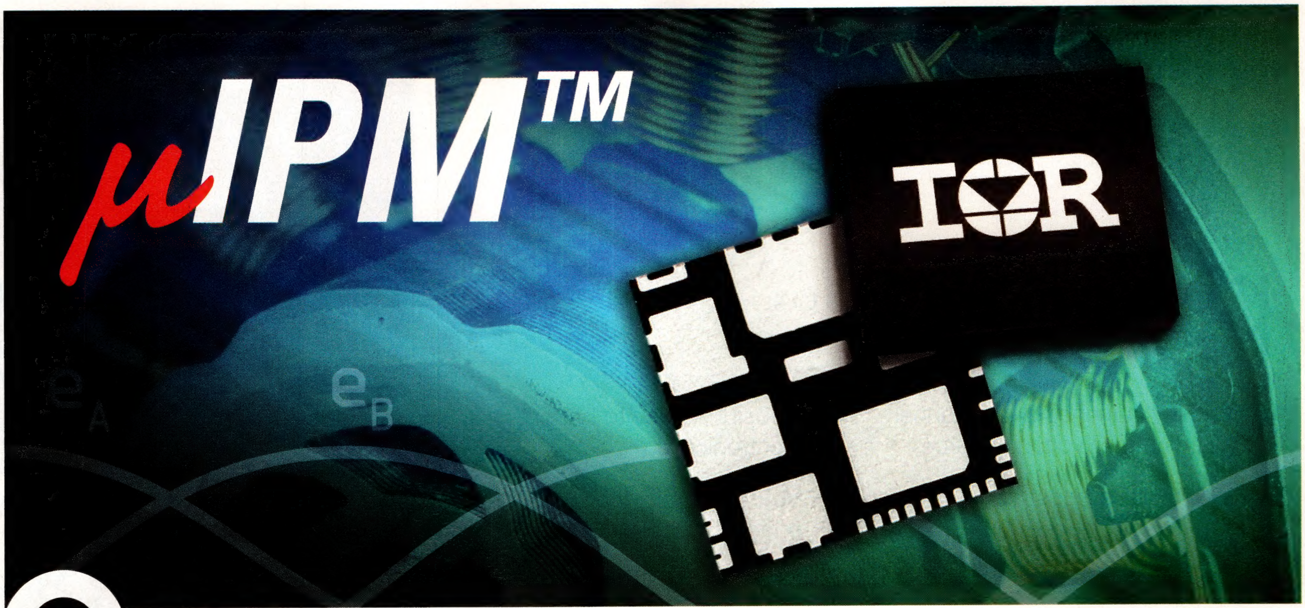

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μIPM™ Power Modules Deliver up to 60% Smaller Footprint

Specifications:

Part Number	Size (mm)	Voltage	IO (DC@ 25°C)	Motor Current**		Motor Power VO=150/75VRMS	Topology
				w/o HS	w/HS		
IRSM836-024MA	12x12	250V	2A	470mA	550mA	60W/72W	3P Open Source
IRSM836-044MA	12x12	250V	4A	750mA	850mA	95W/110W	3P Open Source
IRSM836-025MA	12x12	500V	2A	360mA	440mA	93W/114W	3P Open Source
IRSM836-035MB	12x12	500V	3A	420mA	510mA	108W/135W	3P Common Source
IRSM836-035MA	12x12	500V	3A	420mA	510mA	100W/130W	3P Open Source
IRSM836-045MA	12x12	500V	4A	550mA	750mA	145W/195W	3P Open Source

Features:

- 3-phase motor control IC
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- DC current ratings from 2A to 4A
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***μIPM*™ Advantages:**

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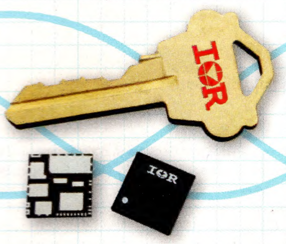

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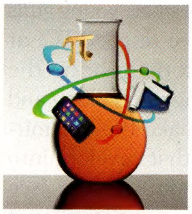
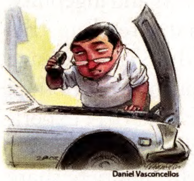
Comments, thoughts, and opinions shared by *EDN*'s community



In response to "Arguments against engineer-supported STEM education," a blog post by Bill Klein at www.edn.com/4398902, Ducksoup_SD commented:

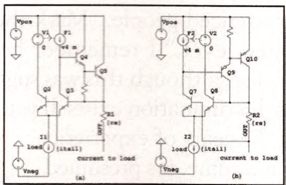
"When industry, government, and society finally decide to respect and reward our talents instead of joking about the hard work we did to give them the tools to mock us publicly worldwide, then—and only then—will the tide turn. Otherwise, you and the rest of the STEM [science, technology, engineering, and math] advocates will simply be tilting at windmills and flushing tax money down the drain."



In response to "But I only need the switch!" an entry by Walter Sjursen in *EDN*'s Tales from the Cube blog at www.edn.com/4398913, zeeglen commented:

"Isn't it nice to be engineers with the time, patience, and know-how to sniff out intermittent [bugs] like these? Can't see how a shop mechanic would be able to diagnose these problems."

In response to "The Class i low-distortion audio output stage (Part 2)," a how-to article by Kendall Castor-Perry at www.edn.com/4398669, Guru of Grounding commented:



"I'm impressed by the elegance ... and simplicity ... of this design. As Einstein once said, 'Everything should be as simple as possible, but no simpler.'"

EDN *invites all of its readers to constructively and creatively comment on our content. You'll find the opportunity to do so at the bottom of each article and blog post.*

CONTENT

Can't-miss content on EDN.com

RESISTORS IN AERONAUTICS APPLICATIONS: MEETING THE NEW PERFORMANCE REQUIREMENTS

This article looks at the different resistor types for aeronautics applications and their required parameters, including high-temperature capabilities for stringent operating conditions, long-term stability, low TCR, and tight tolerances.

www.edn.com/4399171

APPLE'S TOP 10 WORST PRODUCTS

An engineer analyzes the worst 10 Apple products he's had the misfortune to own and use.

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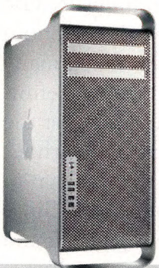

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BY SUZANNE DEFFREE, EXECUTIVE EDITOR

You're old. Get over it.

We all know it's out there. Lingering. Waiting to impede. Still, I wasn't expecting it for at least another five years. I've heard it hits women earlier than men, but now, already? And on my birthday, too. Ouch.

While I was having coffee with a longtime friend, who also happens to have been one of my first managers, an open position at her company came up in conversation. She and I have maintained a good relationship since I worked for her back in the 1990s. We make an effort to follow each other's careers, even though we haven't worked together in more than 15 years.

My friend wondered if I knew of anyone for the job and said, "We're looking for someone just like you, who can do all you can do, except young."

Excuse me?

I pointed out that, having just blown out the candles on my 35th birthday cake, I am young, or at least on the younger side. Certainly not old.

Now, I have to admit, I had watched an episode of *Matlock* that morning, I knew there was a storm coming because of some knee pain, and, yeah, the photo at the top of this page was taken many moons ago when I was, by most definitions, young. But old, no. Not over the hill, not stuck in my ways, not without the spirit and attributes many assign to youth: ability to learn quickly, willingness to experiment with new ideas and to conform to new corporate cultures, freshly educated, up on the latest processes. Whether I had just turned 35, 45, 65, or 85 was not the point. These attributes are not defined by one's age on a driver's license but by mindset and dedication to one's career.

My friend's reply was short but not sweet: "You're old. Get over it."

My coffee had turned bitter and so had I. If she wanted someone who could do all I could do, she wanted someone with more than a decade's worth of experience. You don't get that in a 20-year-old.

Just a few years after I had worked with this woman, and in between full-time jobs, I worked with a career strategist and wrote resumes for some very experienced people. "Mask their experience level," I remember being told because, although this was sugarcoated, age discrimination exists. If you list 20 years of experience on a resume, it's presumed the candidate is either at too high a salary level or out of touch—just plain old.

In the time that has passed since this page's headshot was taken, I've been honing my craft, solving problems, working with engineers and other editors on a daily basis to grow my experience. I've become a more well-informed force than I was at the start of my career.

Unfortunately, we live in a world of Mark Zuckerbergs, where the flashiest new idea often comes from someone not old enough to remember the Reagan years, let alone be born before them. These shining stars are allotted tremendous power and influence over industries. I'm scratching my head, first gray hairs and all, and wondering why.

Why value the inexperience and ignorance that often accompanies youth? Why not hold higher the experience, knowledge, and sharpened creativity that come only from decades of work in a field?

There are plenty of smart young guns out there who deserve respect. We at *EDN* often make efforts to bring the next generation of engineers along and encourage them to make the commitment to engineering that develops into 20, 30, or more years in a career (see "Engineering the next generation of STEM," www.edn.com/4369012). But for the current generation of engineers, it's a disturbing fact that age discrimination undervalues know-how and insults the importance of careers and ingenuity.

I suspect that many reading this column have been the victim of age discrimination in some form or another. Even in such a minor brush as I experienced over my birthday coffee, age discrimination hinders the ability to share experience and knowledge. Ultimately, that dampens the strength of employees and weakens the field of engineering.

In recent weeks, two electronics-industry veterans have announced plans to retire after long, stellar careers during which they made massive contributions to electronics: TI's Gene Frantz (see, "Gene Frantz, TI Principal Fellow and DSP visionary, to retire in February," www.edn.com/4399106), and Avnet's Roy Vallee, whom we spoke with for *EDN*'s October issue. As Vallee pointed out then, "Design careers are marathons, not sprints" (see www.edn.com/4398412).

Let's honor and recognize those who run the marathon over decades, who have proved their strengths and dedication to engineering and design, not just those starting the race. What do you think? Share your thoughts at www.edn.com/4399410. **EDN**

Contact me at suzanne.deffree@ubm.com.

Keithley launches dual-channel picoammeter/voltage source

Keithley Instruments Inc has introduced a dual-channel picoammeter with dual ±30V independent, nonfloating bias sources and measurement resolution of 1 fA. The Model 6482 picoammeter provides two independent picoammeter/source channels in a 2U, half-rack enclosure, allowing simultaneous 6-1/2-digit measurements across both channels. At 4-1/2-digit resolution, users can take up to 900 readings/second on each channel.

With the use of GPIB cables, users can control four instruments simultaneously. The device is well suited for applications where you want to test multiple diodes in a single package or quickly calibrate laser diodes.

Key features include measurement accuracy of ±1% on the 2-nA range. Dynamic range is 1 fA to 20 mA, and dynamic measurement range is 2 nA to 20 mA in decade steps.

Applications include manufacturing, multipin, and semiconductor component testing; dual diode testing; dark current measurements; ion-beam monitoring; and electron microscopy. Users can switch off the front-panel display to avoid introducing light into measurements of photodiodes or other light-sensitive components, acquire ratio or delta measurements between the two completely isolated channels using front-panel or GPIB, and use the Trigger Link feature to control multi-instrument test systems over standard GPIB and RS-232 interfaces.

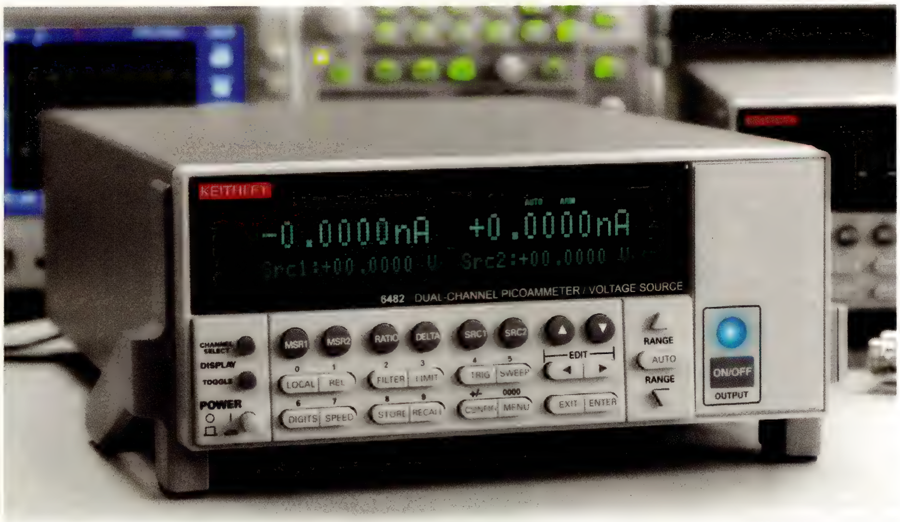
The US list price of the Model 6482 dual-channel picoammeter/voltage source is $3600, with sales beginning immediately. Units will ship from stock or within four weeks ARO. **—by Janine Love**

Keithley Instruments Inc, www.keithley.com

TALKBACK

"But one processor *does* rule them all. It's that thing between our ears. You may fault its reliability and speed—but it's adaptive, self-programming, amazingly creative, and not so bad on the low-power front."

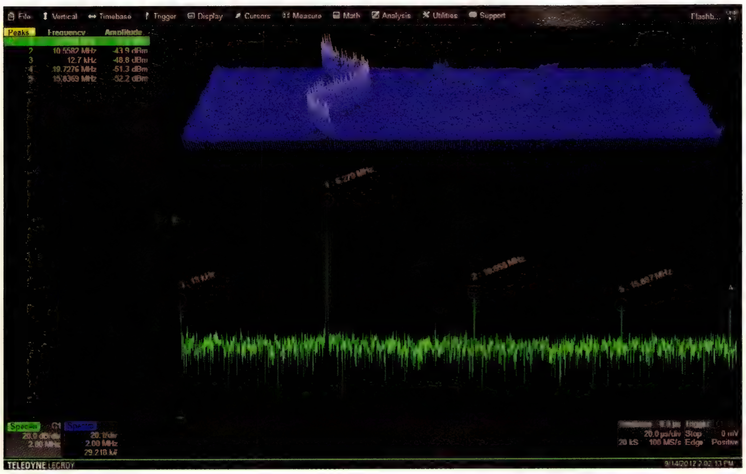
—Commenter CCarpenter, in response to the article "One processor to rule them all?" at www.edn.com/4398890. Add your own comment.



The Keithley Instruments Model 6482 picoammeter provides two independent picoammeter/source channels in a 2U, half-rack enclosure.

12-bit HDOs boost bandwidth, sell at 8-bit prices

When LeCroy—now Teledyne LeCroy—announced its 12-bit-resolution HRO (high-resolution oscilloscope) line approximately 18 months ago, it knew that, as useful and as innovative as the instruments were, their pricing would confine them to niche markets, such as work on switch-mode power supplies. So the company's engineers returned to their lab benches to develop a cost-centric design that would deliver 12-bit resolution (15 bits with the built-in extended-resolution mode) but would compromise neither product features nor quality and could compete on price with instruments having industry-standard 8-bit resolution. The result is a new line, the HDO (high-definition oscilloscope) family, which not only meets (and in several cases, beats) the pricing of competitors' equivalent-bandwidth 8-bit models but also increases the bandwidth of its two top-of-the-line models by more than 50% to 1 GHz. Maximum real-time sampling rate is 2.5 GHz (versus 2 GHz in the HROs). At the lowest price point, LeCroy has added 200-MHz-bandwidth units.



Using the FFT-based spectrum-analysis capability, instruments in the HDO 6000 family (and, optionally, those in the lower-priced HDO 4000 family) can graphically display how RF spectra vary with time. The blue trace at the top shows a spectral peak whose center frequency varies sinusoidally.

The HDO design sacrifices only one HRO feature—the pivoting screen, which allowed users to trade screen width for screen height. The new screen is a 12.1-in. diagonal, 800×1200-pixel, multi-touch-capable unit that permits software upgrades that will enable the use of gestures, such as pinching, to adjust the size of displayed waveforms. The new models cut the occupied bench area almost in half, primarily by reducing the cabinet depth.

LeCroy's engineers have also improved the 12-bit scopes' FFT-based spectrum-analysis capability. According to the company, though covering much less bandwidth than do the spectrum-analysis capabilities of Tektronix's MDOs (mixed-domain oscilloscopes), LeCroy's spectrum analysis is unmatched in competitive units and is included in the prices of the three-model HDO 6000 series. Spectrum analysis is a $2000 option on the lower-priced, six-model HDO 4000 series.

Another unusual feature is the input amplifier, which lets you suppress large dc offsets—as much as ±400V, depending on the voltage range. Hence, without invoking ac coupling, you can use the scope's full resolution to examine the time-varying portion of signals that consist of low-amplitude ac superimposed on high-amplitude dc.

> The HDO family increases the bandwidth of its two top-of-the-line models by more than 50% to 1 GHz.

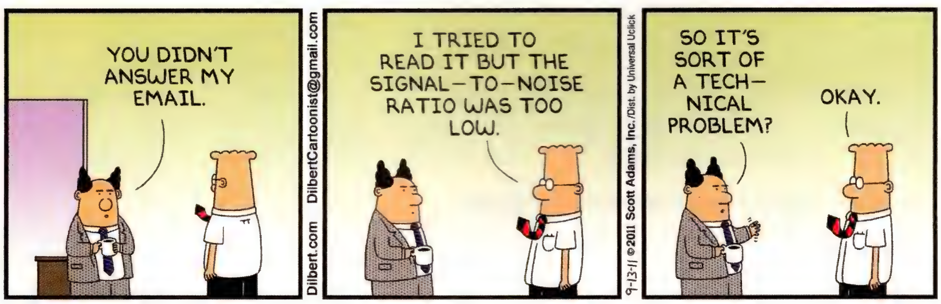
Base US prices for HDO 4000 units with bandwidths of 200 and 350 MHz range from $9000 to $13,500. Models having two and four channels are available. HDO 4000 units with bandwidths of 500 MHz and 1 GHz are also available, but only with four channels; the 1-GHz unit costs $16,400. The HDO 4000-series interleaved mode doubles the acquisition memory depth but not the sampling rate. Standard memory depth is 12.5M samples/channel without interleaving and 25M samples with interleaving. Increased memory depth, to 25/50M samples, is optional.

All HDO 6000 units—with bandwidths of 350 MHz, 500 MHz, and 1 GHz—have four channels. Base US prices range from $14,900 to $19,900. Standard memory depth is 50M samples/channel. Memory interleaving is not offered. Optionally, you can increase the memory depth to 100M or 250M samples/channel.

—by Dan Strassberg

▷**Teledyne LeCroy**, www.teledynelecroy.com

DILBERT By Scott Adams

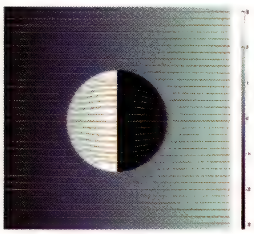


“Invisibility” key to better electronics?

Massachusetts Institute of Technology researchers are extending visual “cloaking” concepts to enable more efficient electron transfer. Letting particles “hide” from passing electrons, they say, could yield more efficient thermoelectric devices and new types of electronics.

The composite metamaterial structures that have been used to cloak objects from view cause light beams to bend around an object and then meet on the other side, resuming their original path and thus making the object appear invisible. For their electron-cloaking material, the MIT researchers modeled nanoparticles with a core of one material and a shell of another. Rather than bend around the object, however, the electrons pass through the particles. The electron paths are bent as they enter a particle and are subsequently bent back so that they emerge from the other side along their initial trajectory, as if the particle weren’t there.

The impetus for the work was to optimize the materials used in thermoelectric devices, which require both high electrical conductivity and low thermal conductivity. The team says its computer simulations show that the electron-cloaking material could meet those requirements unusually well. Next, the team will build devices to see whether they perform as expected.



The diagram shows the “probability flux” of electrons as they pass through an “invisible” nanoparticle. The electron paths are bent as they enter a particle and are subsequently bent back so that they emerge from the other side along their initial trajectory (courtesy Bolin Liao et al).

The concept was developed using particles embedded in a normal semiconductor substrate, but the researchers also want to see whether the results can be replicated with other materials, such as two-dimensional sheets of graphene, which might offer additional properties.

The simulations used particles a few nanometers in size, matching the wavelength of flowing electrons and reportedly improving the flow of electrons at particular energy levels by orders of magnitude compared with traditional doping strategies. That approach might lead to more efficient filters and sensors, according to the researchers.

The concept could also enable switches that would operate by toggling between transparency and opacity to electrons. “We’re not sure how far this is going to go yet, but there is some potential” for significant applications, says MIT mechanical engineering professor Gang Chen.

The US Department of Energy funded the research through MIT’s Solid-State Solar-Thermal Energy Conversion center.

—by Diana Scheben

MIT, web.mit.edu

VOICES

Pulsic: the bleeding edge of custom IC design

If you do custom chip design, you probably know Pulsic, an EDA company based in England that provides floorplanning, placement, and routing solutions for extreme design challenges at advanced nodes. Complementary to existing design flows, Pulsic works with companies that have traditionally preferred handcrafted design methods; it promises faster and higher-quality results compared with general-purpose EDA software solutions. Mark Williams, co-founder and CEO of Pulsic, recently spoke with *EDN*. Excerpts of that conversation follow, with a focus on analog and memory.

How did you come to start Pulsic?

A I was one of the developers of our original core technology, and the founding team actually came out of a company you might remember: Racal-Redac. A couple of the founders were responsible for the world's first shape-based router, which was back in 1985. The cornerstone of the company continues to be shape-based techniques. We have expanded the product line of the company to cover chip planning, placement, and routing for the whole custom spectrum. Today, we try to be the complete custom company, and what I mean by *custom* is everything that basically isn't a standard RTL-to-GDSII digital ASIC flow.

So that's how you compete against the big three?

A We only compete against Cadence because, in the custom world, the golden standard has always been to do it by hand, in Virtuoso. Synopsys has been trying to break in on that monopoly with the Galaxy Custom Designer.

We live with Cadence and are in their connection program. In the memory market, this has been particularly good for us. Memory has unique custom requirements, which means you can't really shoehorn it into an ASIC flow. For example, you have a 21:1 aspect ratio with two metals, highly resistive gates, etc. ASIC tools can't do a good job of that, and we've developed specific custom tools to do a really good job in memory, and it's been our mainstay; it's been our cash cow. We've been very successful automating what was a manual approach to the layout of memory.

What are you investing in?

A We are putting a lot of effort into transistor layout. Transistor layout in analog has long been seen as the Holy Grail of automation. Nobody has done a successful job of really automating analog layout. And truly it comes down to what we call precision design automation.

It's not a question of just automating a design in terms of getting it done in the analog market. The average designer will look at it and say, "OK, yeah, it's placed and it's routed, and it even meets my parasitics, my resistance capacitance," but there's no way the analog designer will take those results, because how it is laid out matters; it really is a handcrafted piece of work that the analog designers do. And getting an automated method or a methodology to give an analog designer a layout that he can [approve of], I would do that kind of layout by hand; that is what's been the Achilles' heel. But we are excited about some technology we've got in this space. We hope that by next year we will have place-and-route technology for the analog space that will really deliver what we believe will be full hierarchy layout for analog design. And of course, it's got some killer interactive stuff in there, as well, that you have to have.

Analog hasn't been scaling quite as nicely as digital for some time. What technologies are most people now using for custom analog?

A A lot of custom analog is being done on older technologies. The reason many people are not moving to the newer nodes is the extra and more complex design rules and constraints that they have to consider (by hand), and this restricts them from moving. It's a bottleneck. If there were more analog automation, you would see more analog designs rushing toward the newer technologies.

Will we ever get to a notion of analog synthesis?

A *Synthesis* is not the right word for analog really, because it's a schematic-driven environment. I don't think we will get to a sort of high-level RTL description of analog in the near future, so realistically what you're talking about is generating a layout from a schematic and doing everything thereafter.

So you don't think that we're ever going to be able to go from an analog behavioral language?

A Maybe. I don't foresee that anytime soon, though, no. You also have to see that we are a physical design company and not moving into the front end.

What advice would you have for somebody thinking of starting an EDA company?

A Be realistic. If you are a virgin EDA start-up, like we were, don't think that you can take a piece of technology to market and it will all fly. It won't. Customers will shoot you down in flames, so you have to have a passion for it. You'll have to work hard and develop continually to get to a point where your product really offers the advantages and returns so that customers will stop doing things the old way and take on your new technology. **—interview conducted and edited by Brian Bailey**

BY HOWARD JOHNSON, PhD

Body and soul

The Athenian school of classical Greek history emphasized three modes of learning: academic, physical, and aesthetic. All three were considered necessary parts of a complete education.

If you work in the field of digital electronics, you probably do OK with academic subjects such as reading, writing, and math. How you stack up physically depends on whether, like me, you spent years hunched over a lab bench eating doughnuts, but that is not my main point. I would like you to consider, just for a moment, your aesthetic training.

IMAGE: JING WANG, COURTESY OF MOLLIE HUNT

I'm not talking about taking a class in art history or basket weaving. I mean for you to consider studying, perhaps with an eye toward mastering, a deep, meaningful type of aesthetics—the sort of subject that affects your soul.

Take, for example, music. Rhythm, intonation, and harmony form only the beginning of musical study. A good musician works in layers, starting with a superior understanding of his instrument. A violinist, for example, studies instrument construction, vibration, resonance, and directionality. He knows the effects of temperature, humidity, age, wood, and varnish; the properties of strings, glue, horse hair, and rosin; and other factors. Onstage, his notes and chords combine with melody to form phrases, and from phrases he crafts larger sections and then complete works. His ability to connect with an audience requires a mastery of stage blocking, room acoustics, lighting, posture, attire, and tradition, along with less tangible qualities of personality, charm, and grace. A good musician simultaneously applies all levels of this knowledge in real time under stressful conditions.

Music stimulates parts of your brain critical to creativity and insight.

Engineers tackle similar tasks. We also work in layers, starting at the atomic level of semiconductor physics and moving up through the design of active devices, then gates, registers, CPUs, whole computer systems, firmware, operating systems, high-level programming languages, and applications. The competent design of a digital masterpiece requires knowledge of packaging, power, crosstalk, ringing, cabling, connectors, PCB design, international standards, and other factors. We apply this knowledge in real time, under stressful conditions.

I find the duality fascinating. Look for it in other fields of human endeavor. The ability to work in layers, to manage tasks of almost unimaginable difficulty, is the hallmark of human excellence. My friends who are musicians engage in such work on a daily basis—as do you.

Even if you never master a musical instrument to the point of performing onstage, the simple act of learning to play music stimulates parts of your brain critical to creativity and insight. If you studied music as a child, you may discover that your powers of concentration are much greater now than they were then. Dreaded practice sessions are transformed into enjoyable time spent pinpointing and overcoming your limitations. Self-study promotes self-introspection and improvement in all areas.

So what's the difference between a musician and an engineer? Note this: Professional musicians spend four to eight hours a day in practice and rehearsal. They practice with an intensity akin to your college experience, only their education continues *every day*.

Imagine how good you would get at your craft if you worked that hard at it. EDN

Howard Johnson, PhD, donates the use of his barn and facilities, located high in the mountains of eastern Washington state, for a series of professional chamber-music concerts every summer (www.methowmusicfestival.org).

BY BONNIE BAKER

What does "rail to rail" input operation really mean?

A hot discussion topic with single-supply operational amplifiers is whether they are capable of rail-to-rail input or output operation. Vendors of single-supply op amps claim their amplifiers have rail-to-rail input capability, but the chip designer has to make some compromises to achieve this type of performance.

A common single-supply amplifier input topology has parallel PMOS and NMOS differential input stages, combining the advantages of those stages to achieve actual rail-to-rail input operation (**Figure 1**). When you bring $V_{IN}+$ toward the negative rail, the PMOS transistors are completely on, and the NMOS transistors are completely off. When you bring the input terminals to the positive rail, the NMOS transistors are in use, and the PMOS transistors are off.

Although the precision, low-power OPA344 input stage in **Figure 1** has rail-to-rail input operation, there are performance compromises that the circuit designer must address. The design topology in **Figure 1** can have wide variations in offset voltage across the amplifier's common-mode input range. In the region near ground, the PMOS offset-error portion of the input stage is dominant. In the region near the positive power supply, the NMOS offset error dominates.

The best way to view the input stage's behavior is to look at the offset voltage versus the common-mode input voltage (**Figure 2**). The 4.6-MHz, rail-to-rail input/output LMP7701 CMOS amplifier in **Figure 2** exhibits the offset-voltage-error crossover behavior around 1.4V. At lower common-mode input voltages, the PMOS transistors are in operation, with the NMOS transistors turned off. At approximately 1.1V, the NMOS transistors start to turn on. As the common-mode input voltage increases, the NMOS section of the circuit finally takes over, with the PMOS transistors completely off. From approximately 1.1 to 2V, both the PMOS and NMOS transistors are operating.

There are circuit-design tricks at your disposal for minimizing this input-stage crossover effect; you can read about them in "Rail-to-rail input amplifier application solutions" (www.edn.com/4400221).

Single-supply amplifier manufacturers also claim that they have devices that will swing rail-to-rail on the output. With those types of amplifiers, the output cannot go all the way to the rails, but it can get close.

Next time, I'll talk about the rail-to-rail amp's output stage and its ability to achieve rail-to-rail performance. EDN

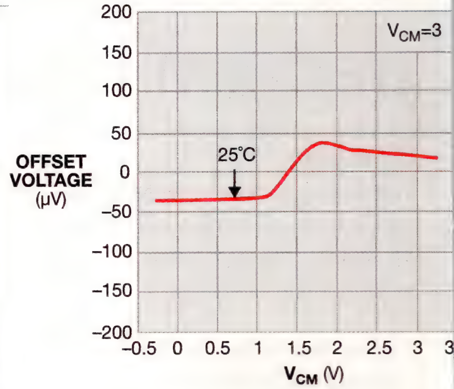


Figure 2 As the amplifier's common-mode voltage changes from ground to the positive supply, the input stage of the CMOS amplifier completely changes from its PMOS input pair to its NMOS input pair at ~2V below the 3V positive supply rail.

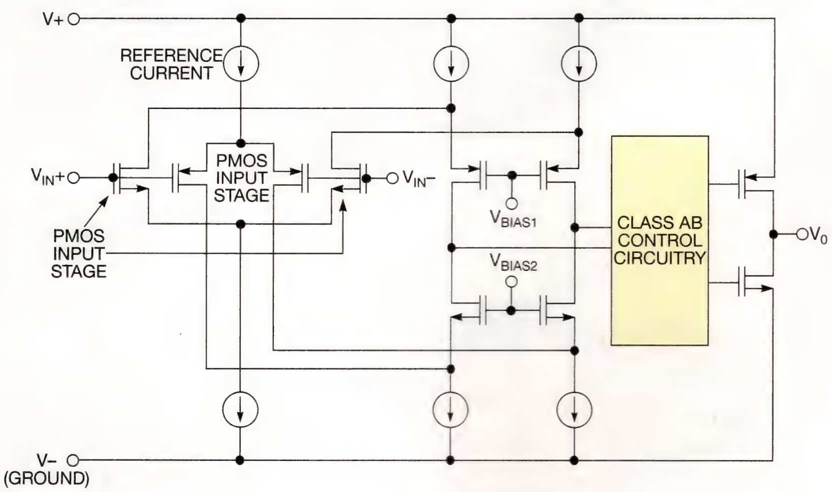


Figure 1 This composite input stage of the op amp uses PMOS and NMOS differential pairs so the input-voltage range can extend from above the positive rail to below the negative rail.

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1 OPA344 data sheet, Texas Instruments, www.ti.com/opa344-ca.

2 LMP7701 data sheet, Texas Instruments, www.ti.com/lmp7701-ca.

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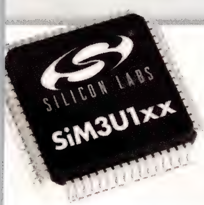

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Cell-phone charger: nice idea, bad implementation

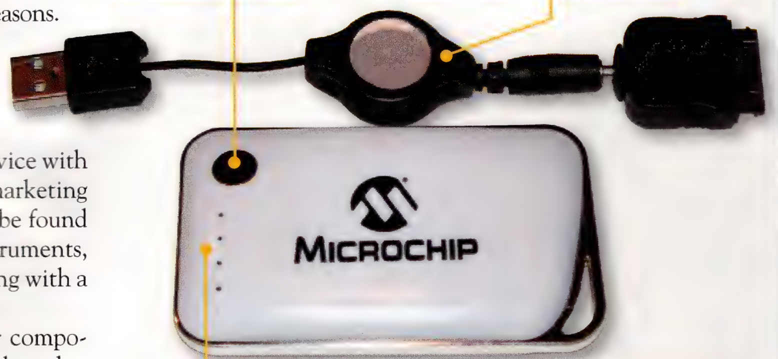
Now and again you come across a device that's so simple, useful, and functional that you're glad to add it to your already-overladen workbag; that is, until it breaks, for the dumbest of design reasons. In this case, I am talking about a cheap USB power connector.

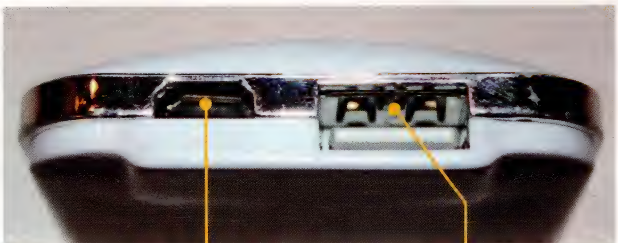
I got one of these devices from Microchip a while back. It's a simple cell-phone backup battery from a no-name Chinese company that emblazoned the device with a Microchip logo. While the idea was good, from a marketing standpoint, it's ironic that no Microchip parts can be found inside. Instead, the main part comes from Texas Instruments, in the form of the LM324 operational amplifier, along with a USB power detector and battery-charging circuitry.

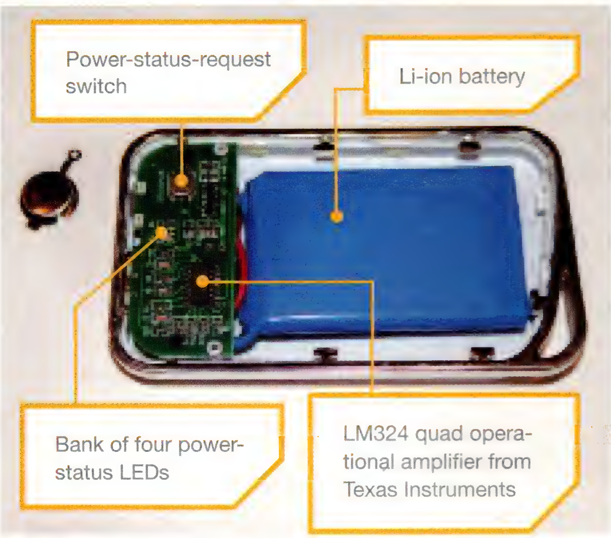
I may need your help ID'ing some of the other components, but a hulking—relative to the size of the board—inductor, as well as a 220-μF, 16V electrolytic capacitor tell me that U1 (labeled DK J8) may be the output transistor for a low-frequency switching power circuit.

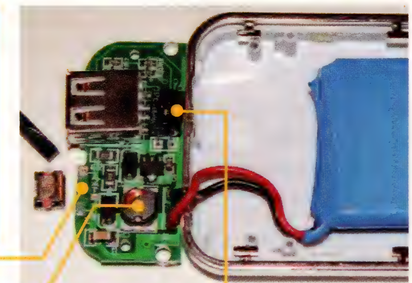
In any case, it's a classic case of a useful device gone bad: A poorly designed mini-USB input power port came detached right when I needed it most. Now the device is useless, unless I can get it soldered on again. Given the size of the solder positions and their location under the connector, a fix does not seem likely. Suggestions for how to do that are welcome. For now, it's an interesting lesson for anyone who thinks the MCU or processor is the most important part of an advanced system. All reverts to naught when the connector breaks!

How often have you seen good devices or designs fail because of silly corner-cutting? Send your photos and story to patrick.mannion@ubm.com; we have to do a collection of these!









Taking that tough first step

The ability to physically model differentiates engineers; it is not a commodity.

By Kevin C Craig, PhD

Can physical system modeling be taught? Is it an art or a science?

Physical system modeling, applied either to an existing system or to a concept in the design process, leads to thorough understanding, differentiates engineers, and gives companies a competitive advantage as it leads to innovation. Many engineers, however, have little experience—and, hence, little confidence—in accomplishing it.

A mathematical model is obtained by applying the laws of nature to the physical model, not to the physical system; the physical model must come first. There is a hierarchy of physical models possible in response to the question, Why am I modeling? Engineering judgment and simplifying assumptions applied to the physical system lead to the physical model, which must capture the essential multidisciplinary attributes of the physical system. A working knowledge of multidisciplinary physics is essential. Always, the best model is the simplest model that meets the need.

Figure 1 shows an internal-combustion engine connected to an eddy-current dynamometer. The physical model is shown in **Figure 2**. The engine is considered a nonlinear angular velocity source (ω_E), modulated by the throttle setting $\theta(t)$. The main energy storage is associated with the rotating inertia, J_E, lumped at the output of the engine shaft. The torque transmission shaft has compliance and energy dissipation, and is modeled with a rotational spring, K_S, and rotational damper, B_S. The shaft inertia is neglected. The dynamometer consists of a toothed rotor, J_R, that rotates (ω_R) in the magnetic field created by passing current $i_f(t)$ through the stator windings.

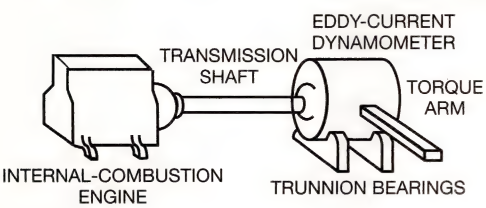


Figure 1 An internal-combustion engine is connected to an eddy-current dynamometer.

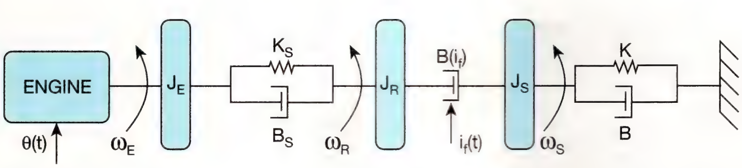


Figure 2 The physical model shows the engine as a nonlinear angular velocity source (ω_E), modulated by the throttle setting $\theta(t)$.

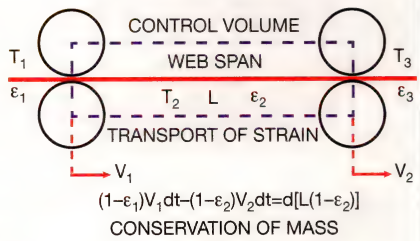


Figure 3 Creating a physical model of a web-handling system is the first step to predicting and controlling both the tension and velocity of the web.

A voltage is induced in the conductive rotor rotating in the stator magnetic field (Faraday's Law). This induced voltage creates eddy currents in the rotor that generate a magnetic field (Ampere's Law), which opposes the stator magnetic field (Lenz's Law). The stator inertia, J_S, mounted in trunnion bearings, is restrained by a torque arm to measure the torque developed. The spring K and damper B represent the compliance and energy dissipation associated with the torque measurement.

Figure 3 shows a portion of a web-handling system between two sets of driven rollers. A physical model is the first step to predicting and controlling both the tension and velocity of the web. What is most interesting here is that a failure to understand the fundamental physics of web transport led to inaccurate modeling for many years. The Law of Conservation of Mass is applied to a control volume encompassing the web span, where the physical model allows for the transport of strain ε from the upstream web span to the downstream span, an essential characteristic validated by experimental observations. T is the web tension, assumed constant in any web span of length L.

Successful physical modeling requires an understanding of multidisciplinary physics and a commitment not to fall back on the old design-build-test approach. That is the clear path to innovation. EDN

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DESIGNING LOW-ENERGY EMBEDDED SYSTEMS FROM SILICON TO SOFTWARE

BY KEITH ODLAND • SILICON LABORATORIES INC

Low-energy system design requires attention to nontraditional factors ranging from the silicon process technology to the software that runs on microcontroller-based embedded platforms. Closer examination at the system level reveals three key parameters that determine the energy efficiency of a microcontroller: active-mode power consumption; standby power consumption; and the duty cycle, which determines the ratio of time spent in either state and is itself determined by the behavior of the software.

A LOW-ENERGY STANDBY STATE CAN MAKE A MICROCONTROLLER SEEM EXTREMELY ENERGY EFFICIENT, BUT ITS TRUE PERFORMANCE IS EVIDENT ONLY AFTER TAKING INTO ACCOUNT ALL OF THE FACTORS GOVERNING ACTIVE POWER CONSUMPTION.

IMAGE: SHUTTERSTOCK

A low-energy standby state can make an MCU seem extremely energy efficient, but its true performance is evident only after taking into account all of the factors governing active power consumption. For this and other reasons, trade-offs among process technology, IC architecture, and software construction are some of the many decisions with subtle and sometimes unexpected outcomes. The manner in which functional blocks on an MCU are combined has a dramatic impact on overall energy efficiency. Even seemingly small and subtle changes to the hardware implementation can result in large swings in overall energy consumption over a system's lifetime.

AT A GLANCE

- Trade-off decisions among process technology, IC architecture, and software construction can yield subtle and sometimes unexpected outcomes.
- Power gating can ameliorate the effects of leakage and make more advanced process nodes better choices for low-duty-cycle systems.
- On-chip voltage regulators provide the system designer with greater flexibility, making it possible to extract more charge from a battery, and on-chip dc/dc converters and performance-monitoring circuits enable dynamic voltage scaling.
- Hardware-aware software tools provide the embedded-systems engineer with greater awareness of what further savings are achievable.

LOW-ENERGY APPLICATIONS

Metering and alarm systems, for example, are often powered for 10 years by a single battery. A small increase in current consumption for a sensor reading (of which hundreds of millions may occur over the lifetime of the product) can result in years being lost from the product's actual in-field lifetime. A simple smoke alarm that detects the presence of smoke particles in the air once a second will take 315 million readings during its life span.

The activity ratio or duty cycle of a simple smoke alarm is relatively low. Each sensor reading may take no more than a few hundred microseconds to complete, and much of that time is spent in calibration and settling as the MCU wakes up the ADCs and other sensitive analog elements and lets them reach a stable point of operation. In this case, the duty cycle is likely to lead to a design that is inactive approximately 99.98% of the time.

A traditional smoke alarm is comparatively simple. Consider a more complex RF design in which a sensor mesh relays results to a host application. The sensor needs to listen for activity from a master node so that it can either signal that it is still present within the mesh network or provide recently captured information to the router. This increased activity, however, may not affect the overall duty cycle; instead, more functions may be performed during each activation period using a higher-performance device. Because of its increased processing speed, made possible by a more advanced architecture and semiconductor technology, the faster device can provide greater energy efficiency than can a slower device running for more cycles. The key lies in understanding the interactions among process technology, MCU architecture, and software implementation.

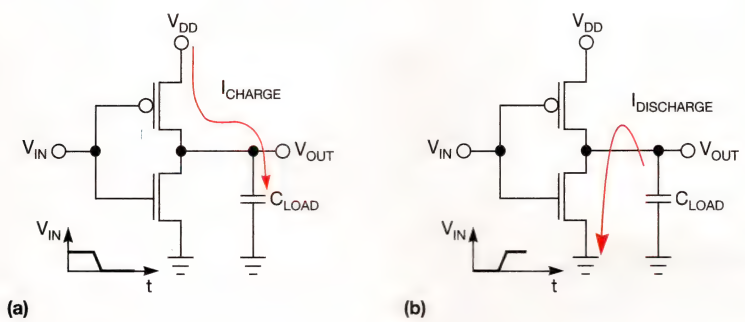

Figure 1 Switching losses of a CMOS logic structure involve charging (a) and discharging (b) a capacitive load.

SILICON CHOICES

CMOS energy profile. Nearly all MCUs are implemented using a CMOS technology (**Figure 1**). The power consumption of any active logic circuitry is given by the formula CV^2f, where C is the total capacitance of the switching circuit paths within the device, V is the supply voltage, and f is the operating frequency. The voltage and capacitance are factors of the underlying process technology. Over the past three decades, the on-chip operating voltage of CMOS logic has fallen from 12V to less than 2V as transistors have scaled down in size. Because voltage is a quadratic function in the active-power equation, the use of lower voltages has a significant impact.

Although the capacitance term is linear, Moore's Law scaling greatly assists in the factors that lead to reductions in its overall level. For a given logical function, a more recent process will offer lower capacitance—and, with it, lower power consumption—than its predecessors. In addition, advanced design techniques enable clock gating, which makes it possible to reduce the overall switching frequency by operating only those circuits with actual work to perform.

Compared with other technologies, CMOS dramatically reduces wasted energy; however, leakage current remains. In contrast to active power consumption, the leakage increases with Moore's Law scaling and must be taken into account in any low-energy application because of the proportion of time that a low-duty-cycle system is inactive. As with active power consumption, however, circuit design has a dramatic impact on real-world leakage. Analogous to clock gating, power gating can greatly ameliorate the effects of leakage and make more advanced process nodes better choices for low-duty-cycle systems, even though an older process technology may offer a lower theoretical leakage figure.

Appropriate process technology. An appropriate process technology exists for every feature set. The answer is not simply to rely on one process technology that has the lowest theoretical leak-

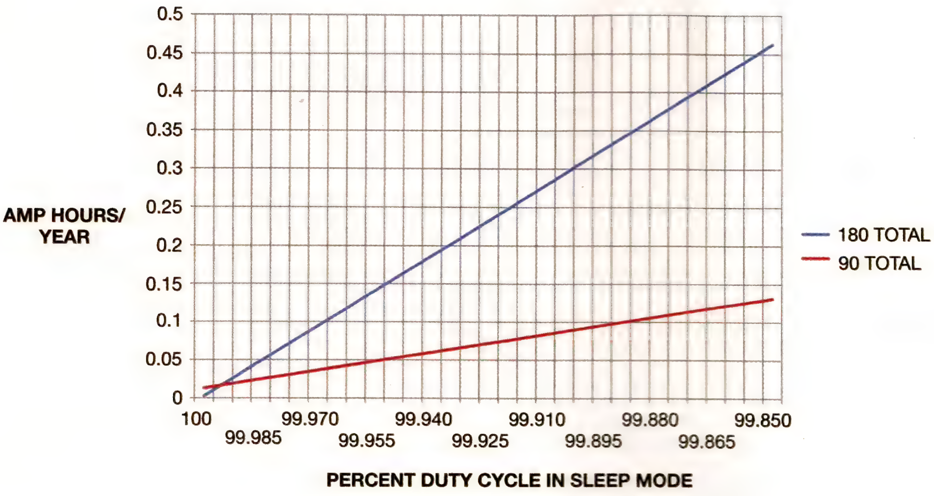

Figure 2 Trade-offs between process technology and duty cycle affect power optimization.

age just because the device will spend a long time in sleep mode. During sleep mode, it is possible to disable power to large segments of the MCU, taking the leakage component out of the equation. Leakage is a bigger issue when circuits are active, but the advantages of advanced transistors that switch far more efficiently can easily offset it.

As an example, the leakage current of a 90-nm process is approximately five times higher than that of a dedicated low-power, 180-nm process. The active-mode power consumption is a factor of four lower, but this is based on a far larger figure.

Take a 180-nm MCU with an active current consumption of 40 mA and a deep-sleep-mode consumption of 60 nA and compare those power levels with the power levels of a 90-nm implementation that is able to drive the active current draw down to 10 mA but draws a higher sleep-mode current, of 300 nA. The MCU must be active 0.0008% of the time for the 90-nm implementation to be more energy efficient overall. In other words, if the system is active for just 1 sec per day, the 90-nm version is approximately 1.5 times as energy efficient as its 180-nm counterpart. The conclusion is that it is important to understand the application duty cycle when selecting a process geometry (**Figure 2**).

Once the appropriate process technology has been selected, the IC designer has

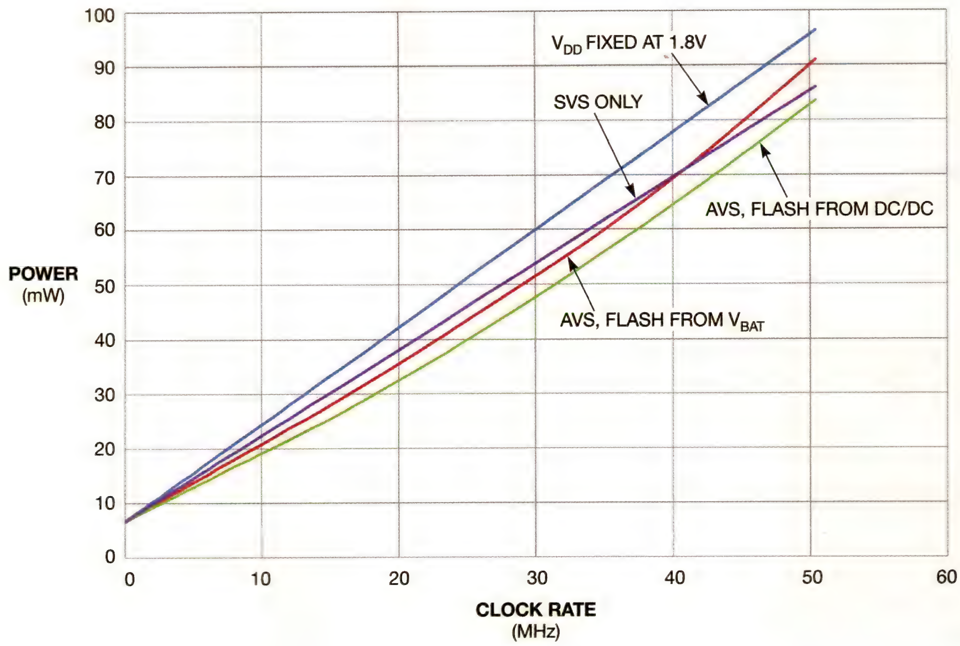

Figure 3 Effects of voltage scaling are shown with V_{BAT}=3.6V.

the option to optimize energy performance further. When it was introduced, the concept of clock gating was applied at a relatively coarse level. Clock gating increases the complexity of a design because the circuit designer needs to be aware of which logic paths will require a clock signal at any given time.

Clock distribution. Most MCU implementations use a hierarchical structure to distribute clock signals and the appropriate voltage levels to each part of the IC. The functional units, such as instruction processing blocks and peripherals, are organized into groups that are each fed by a separate clock tree and power network. A frequency divider or multiplier derives the clock signal for each group from a common clock source. Similarly, if the groups require different voltages—an approach that is becoming increasingly common—a set of power transistors and voltage regulators will deliver the voltage to each group of peripherals.

To minimize design complexity, MCUs have used a relatively simple clock-gating scheme in which entire clock trees are disabled as long as no functional units inside a group are active. This scheme, however, allows logic that is performing no useful work to be clocked in groups that are active. For example, the adder unit in a CPU core might receive a clock even if the current instruction is a branch. The switching triggered by the clock signal within that adder increases power consumption by a factor of CV^2f, as described earlier.

Improvements in design tools and techniques have made it possible to increase the granularity of clock gating to the point where no peripheral or functional unit receives a clock signal if it has no work to perform during that cycle.

Voltage scaling provides further potential energy savings by making it possible to deliver a lower voltage to a particular group of functional units when required. The key to delivering the appropriate voltage to a group of functional units or peripherals lies in the implementation of on-chip voltage regulators or dc/dc converters and the use of monitoring circuits to ensure that the IC operates at the required voltage.

Power-supply considerations. On-chip voltage regulators provide the system designer with greater flexibility, making it possible to extract more charge from a battery. For example, an on-chip switching buck converter, as in Silicon Labs' SiM3L1xx MCU products, can be used to take the 3.6V of an industrial battery and convert it to 1.2V at more than 80% efficiency. Many MCUs do not have this feature and use linear components to drop the voltage to the right level with a greater degree of waste. In advanced implementations, the buck regulator can be switched off when the battery has discharged to such a level that it no longer makes sense to perform the conversion. As a result, the power supply can be optimized for energy efficiency over the lifetime of the device, all under software control.

SOFTWARE DECISIONS

Performance scaling. Implementing energy-efficient embedded applications relies on software design that uses hardware resources in the most appropriate way. What is appropriate depends not only on the application but also on the hardware implementation. Likewise, the more flexible the hardware in terms of CPU, clock, voltage, and memory usage, the greater the potential energy savings the developer can achieve. Hardware-aware software tools provide the embedded-systems engineer with greater awareness of what further savings are achievable.

One option is to employ dynamic voltage scaling, as shown in **figures 3** and **4**. On-chip dc/dc converters and performance-monitoring circuits enable this technique by providing the ability to reduce the supply voltage when the application does not need to execute instructions at the highest speed. Under those conditions, the system operates with reduced power consumption. The

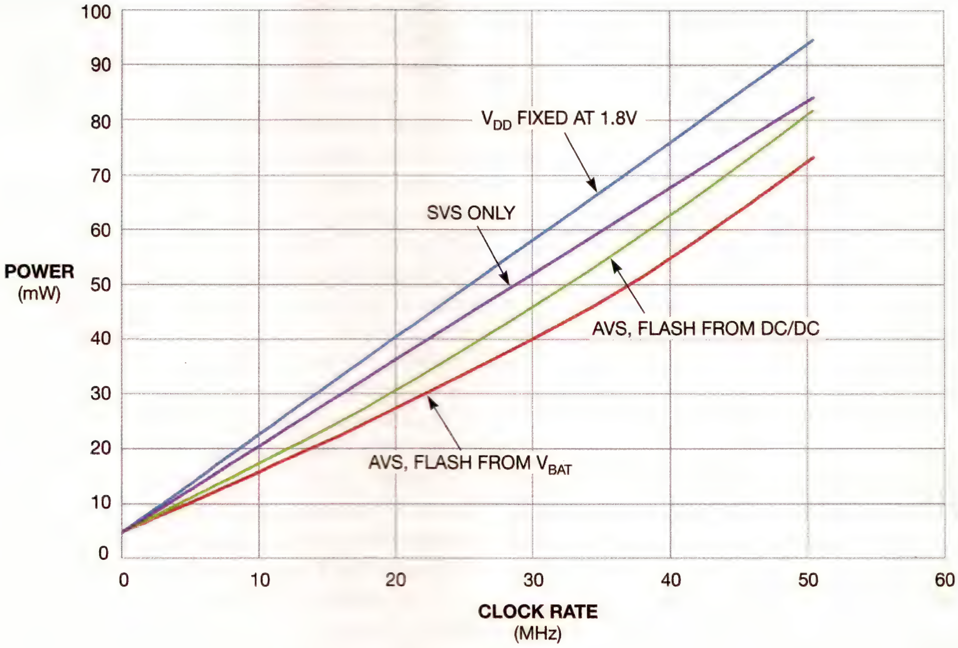

Figure 4 Effects of voltage scaling are shown with V_{BAT}=2.4V.

resultant benefits are a function of input voltage and can vary over the life of a product. The **figures** show the relative differences between no voltage scaling (V_{DD} fixed), SVS (static voltage scaling), and AVS (active voltage scaling).

An interesting artifact of AVS is that the AVS strategy can change depending on the input voltage to the system. In

this example, when the input voltage is 3.6V, it is more efficient to power the internal logic as well as the flash memory from a high-efficiency internal dc/dc converter. As the input voltage falls as a result of battery discharge over the product life cycle, however, it is more efficient to power the flash-memory subsystem from the input voltage directly because the internal logic can operate at lower voltages than the memory. The SiM3L1xx MCU family from Silicon Labs, for example, has a flexible power architecture with six separate and variable power domains to enable this kind of dynamic optimization.

THE ADDITION OF HARDWARE BLOCKS SUCH AS DMA CAN FURTHER CHANGE THE ENERGY TRADE-OFFS.

Typically, CMOS logic circuits will operate more slowly as their voltage is reduced. If the application can tolerate lower performance—as is often the case when dealing with communications protocols that demand data be delivered no faster than a certain standardized frequency—then the quadratic reduction in energy consumption with lower voltage can provide large energy savings. Leakage provides a lower limit on voltage scaling. If each operation takes too long, leakage will begin to dominate the energy equation and increase overall energy consumption. For that reason, it can make sense to execute a function as quickly as possible and then put the processor into sleep mode to minimize the leakage component.

Consider a wireless sensor application that needs to perform a significant amount of digital signal processing, such as a glass-breakage detector. In this example, the application uses a fast Fourier transform to analyze the vibrations picked up by an audio sensor for the characteristic frequencies generated by glass shattering. The FFT is relatively complex, so executing it at a lower frequency governed by a reduced voltage is likely to increase leakage substantially, even in older process technologies. The best approach, in this case, is to execute at near maximum frequency and then return to sleep until the time comes to report any findings to a host node.

The wireless-protocol code, however, imposes different requirements. Radio protocols have fixed timings for events. In these cases, the protocols can be handled entirely in hardware. It makes more sense to reduce the processor core's voltage. Therefore, the code needed for packet assembly and transmission runs at a speed appropriate to the wireless protocol.

The addition of hardware blocks such as intelligent DMA (direct memory access) can further change the energy trade-offs. Many DMA controllers, such as the one provided by the native ARM Cortex-M3 processor, require frequent intervention from the processor. More intelligent DMA controllers that support a combination of sequencing and chaining, however, let the processor compute packet headers, encrypt data, assemble packets, and then hand over the work of passing the packets at appropriate intervals to the memory buffers used by the radio front end. For much of the time that the radio link is active, the processor can sleep, saving significant energy.

Memory usage. With modern 32-bit MCUs, software engineers have a high degree of freedom in the way memory blocks are used. Typically, the MCU will provide a mixture of nonvolatile flash memory, for long-term code and data storage, and SRAM, to hold temporary data. In most cases, the power consumption of flash accesses will be higher than those made to SRAM. In the normal usage case, flash reads exceed SRAM reads by a factor of three. Flash writes—which require entire blocks to be erased and then rewritten using a lengthy sequence of relatively high-voltage pulses—consume even more power. For most applications, however, flash-write operations are infrequent and do not materially affect the average power consumption.

A further factor in flash-memory power consumption is how accesses from the processor are distributed. Each flash block contains multiple pages, each of which can be up to 4 kbytes in size. To support accesses, each page has to be powered up; any unused pages can be maintained in a low-power state. If a regularly accessed section of code straddles two flash pages rather than being contained within one, then the energy associated with instruction reads will increase. Reallocating memory to place frequently accessed sections of code and data within discrete pages can result in sizable savings in power consumption over the lifetime of a battery charge, with no changes to the physical hardware.

It often makes sense to copy functions that are used more frequently into on-chip SRAM and read their instructions from there rather than from flash, even though this approach appears to use the memory capacity less efficiently. The benefit in battery life can easily offset the slightly higher memory consumption.

Code optimization. Energy optimization can also upend traditional ideas of code efficiency. For decades, embedded-system engineers have focused on optimizing code for memory size except when performance is critical. Energy optimization provides an altogether new set of metrics. An important consideration is usage of the on-chip cache that is generally available to 32-bit platforms.

Optimization for code size enables retention of more of the executable in cache, which improves both speed and energy consumption. However, function calls and branches, used to reduce the size of the application by enabling the reuse of common code, can result in unintended conflicts between sections of the code for the same line in the cache. This can result in wasteful "cache thrashing" as well as multiple flash-page activations when the instructions need to be fetched from main memory.

It makes sense for code that runs frequently during the lifetime of the product to be sufficiently compact to fit into the cache but not to branch or call functions. Consider a smoke alarm: Even if the alarm triggers once a week (perhaps from excess smoke caused by activity in the kitchen), that is only 520 events out of 315 million during the alarm's 10-year life. The vast majority of the time, the code takes only a sensor reading, finds that the threshold has

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not been exceeded, and then puts the processor core back to sleep until the system timer awakens it.

Out of all the sensor readings the alarm takes, fewer than 0.0002% will result in the execution of alarm-generating code. The remaining 99.9998% of code execution will be of the core sensor-reading loop; ensuring that this code is run in a straight line out of cache can be the key to minimizing energy usage. The remaining code, because it runs so infrequently, can be optimized using more traditional techniques.

Tools for energy efficiency. Tool support is vital for maximizing the energy efficiency of an MCU platform. The ability to allocate functions to discrete pages of flash memory requires a linker that understands the detailed memory map of each target MCU. The linker can take developer input on whether blocks can be allowed to cross page boundaries and generate a binary that is optimized for the most energy-efficient use of nonvolatile storage.

In principle, this code is also used to ensure that functions and data are placed in such a way that the most commonly executed ones do not clash over cache lines. This level of detail can be achieved much more easily when the MCU vendor—which knows the memory layout and power requirements of each target platform—provides the tools. It is far more difficult for a third-party vendor to achieve.

The MCU vendor also has a detailed understanding of how the different peripherals and on-chip buses are organized. This knowledge can be applied in tools to guide the engineer in making choices that do not waste power. **EDN**

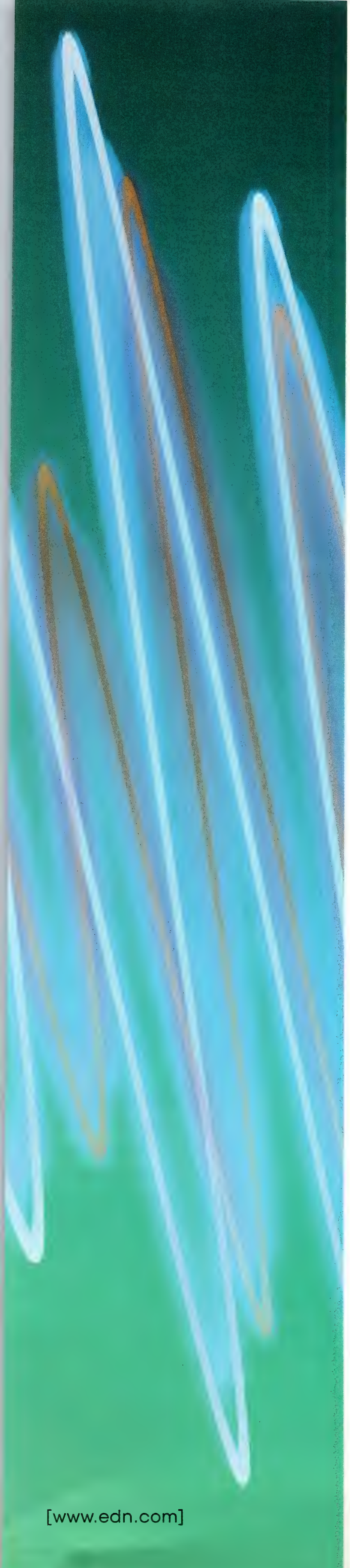
AUTHOR'S BIOGRAPHY

Keith Odland is the director of marketing for Silicon Laboratories' microcontroller products. Before joining Silicon Labs, Odland served as a technical solutions manager for Future Electronics Corp and co-founded Technology Kitchen Corp, where he developed a specialty instrument for the general aviation industry. Odland has also served in engineering- management roles at Dell Computer Corp and Eaton Corp. He holds a bachelor's degree in electrical engineering from the University of Texas at Austin.

CONDITIONING TECHNIQUES FOR REAL-WORLD SENSORS

BY STEVE TARANOVICH

SENIOR TECHNICAL EDITOR



MANY REAL-WORLD SENSORS PRODUCE LOW OUTPUT VOLTAGES AT LOW FREQUENCIES THAT REQUIRE A SIGNAL-CONDITIONING CIRCUIT WITH HIGH GAIN AND ACCURATE—CLOSE TO DC—PERFORMANCE. WE ASSESS THE STATE OF THE ART IN SENSOR SIGNAL CONDITIONING FOR MODERN ANALOG ELECTRONICS.

Modern sensors detect a multitude of real-world analog attributes—temperature, force, pressure, humidity, flow, and power, just for starters. In turn, they typically output some level of voltage, current, charge, or resistive analog signal, or a purely digital signal, in proportion to their respective environmental stimuli. Some sensors operate autonomously; others need power supplied, typically in the form of a voltage or current source. Many times, unique signal conditioning is needed or incorporated to provide a useful electrical output. Here, we look at some state-of-the-art techniques for sensor signal conditioning used in modern analog electronics.

As the need for highly precise operational amplifiers continues to grow, the self-correcting architectures—designs that continuously correct for offset error—have become increasingly popular. Many leading amplifier manufacturers use "zero drift" to refer to any continuously self-correcting architecture, whether it is an auto-zero or a chopper-stabilized topology, observes Kevin Tretter, principal product marketing engineer at Microchip Technology Inc. Typically, chopper amplifiers are better suited for dc or low-frequency applications, whereas auto-zero amplifiers are suitable for wider-band applications.

Tretter notes that auto-zero architectures used for zero-drift signal conditioning contain a main amplifier, which is always connected to the input, and secondary amps that continuously correct their own offset and apply the offset correction to the main amplifier. Microchip Technology has implemented this type of architecture on the MCP6V01, in which the offset error of the main amplifier is corrected 10,000 times/sec, resulting in what Microchip says are extremely low offset and offset drift.

A chopper-stabilized architecture also uses a high-bandwidth main amplifier that is always connected to the input, as well as an "auxiliary" amplifier that uses switches to chop the input signal and provide offset correction to the main amplifier. In Microchip's MCP6V11 low-power amplifier, for example, chopping action minimizes offset and offset-related errors.

Although their internal operation differs, auto-zero and chopper-stabilized amplifiers share the same goal: to minimize offset and offset-related errors. This results in not only low initial offset but also low offset drift over time and temperature, superior common-mode and power-supply rejection, and elimination of 1/f (frequency-dependent) noise.

AT A GLANCE

- Typically, chopper amplifiers are better suited for dc or low-frequency applications, whereas auto-zero amplifiers are suitable for wider-band applications.
- Two very common topologies respectively construct instrumentation amplifiers from two and three op amps.
- Energy harvesting powers a microprocessor or transmitter from a remote location without a local power source.
- Complete solutions need to address sensor drive and output requirements, sample rate, signal-path calibration, performance, sensor diagnostics, and power-consumption needs.
- Wireless sensor networks are changing the way information is gathered, increasing the amount and accessibility of data about the physical world.

CHOPPER ARCHITECTURES

Reza Moghimi, an applications engineering manager with Analog Devices Inc, notes that many real-world sensors produce low output voltages at low frequencies that require a signal-conditioning circuit with high gain and accurate—close to dc—performance. Applications for such sensors include precision electronic scales, load-cell and bridge transducers, interfaces for thermocouple/thermopile sensors, and precision medical instrumentation.

The offset voltage, offset-voltage drift, and 1/f noise of nonprecision amplifiers used for signal conditioning of these sensors cause errors that require hardware or software calibration. Moghimi offers examples of high-precision signal conditioning in which zero-drift amplifiers—designed to achieve ultralow offset voltage and drift, high open-loop gain, high power-supply rejection, high common-mode rejection, and no 1/f noise—benefit designers by eliminating the need for calibration.

The circuit in **Figure 1** uses the AD7791, a low-power buffered 24-bit sigma-delta ADC, along with external ADA4528-x zero-drift amplifiers, in a single-supply precision weigh-scale application. The circuit, built and tested by ADI and described in **Reference 1**, yields 15.3-bit noise-free code resolution for a load cell with a full-scale output of 10 mV and maintains good performance over the full output data range, from 9.5 Hz to 120 Hz.

The differential amplifier in the circuit comprises two low-noise, zero-drift ADA4528 amplifiers with 5.6 nV/$\sqrt{\text{Hz}}$ of voltage noise density at 1 kHz, 0.3-µV offset voltage; 0.002 µV/°C offset-voltage drift; and 158 dB and 150 dB of common-mode and power-supply rejection, respectively. Circuit gain is equal to $1+2R_1/R_G$, and the lowpass filters implemented by placing capacitors C_1 and C_2 in parallel with resistors R_1 and R_2 limit the noise bandwidth to 4.3 Hz, restricting the amount of noise entering the sigma-delta ADC. C_5, R_3, and R_4 form a differential filter with a cutoff frequency of 8 Hz to limit noise further. C_3 and C_4 in conjunction with R_3 and R_4 form common-mode filters with a cutoff frequency of 159 Hz.

Another example of high-precision, low-power signal conditioning is the electrocardiogram circuit shown in **Figure 2** and described in **Reference 2**. The ECG circuit must operate with a differential dc offset because of the half-cell potential of the electrodes. The tolerance for this overvoltage is typically ±300 mV, but in some situations it can be 1V or more. The downward trend of supply voltages in ECG circuits and the presence of this larger half-cell potential limit the gain that can be applied in the first stage of signal conditioning.

The AD8237 architecture solves this problem by connecting a low-frequency inverting integrator from the output to the REF pin that only has to swing as far as the dc offset, instead of the dc offset multiplied by the gain. Because the amplifier applies gain to the integrator output, large gains can be applied at the amplification stage, and the precision requirements of the rest of the system can be reduced. Noise and offset error from devices after this amplification in the signal path contribute less to the overall accuracy. The AD8607 dual micropower instrumentation amp, with 115 µA of supply current, is used for integration, buffering, and level shifting. Proper decoupling is not shown.

The zero-drift, rail-to-rail input and output instrumentation amplifier can operate with a minimum supply voltage of 1.8V, gain drift of 0.5 ppm/°C, and offset drift of 0.2 µV/°C. Two external resistors set gain range from 1 to 1000. The AD8607 can fully amplify signals with common-mode voltage at or up to 300 mV beyond its supplies.

APPLICATIONS

Microchip's Tretter notes that when chopper-stabilized amplifiers first came

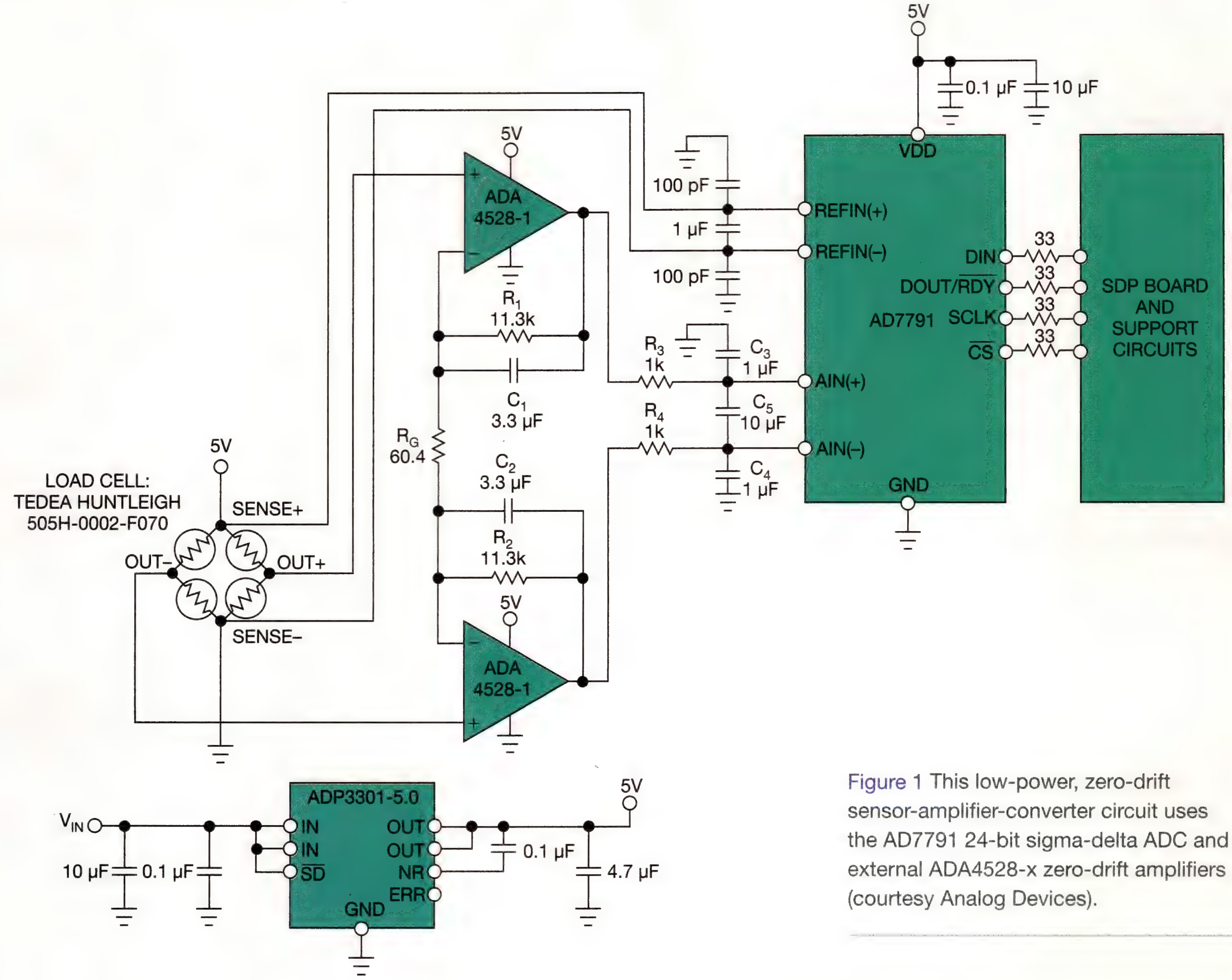


Figure 1 This low-power, zero-drift sensor-amplifier-converter circuit uses the AD7791 24-bit sigma-delta ADC and external ADA4528-x zero-drift amplifiers (courtesy Analog Devices).

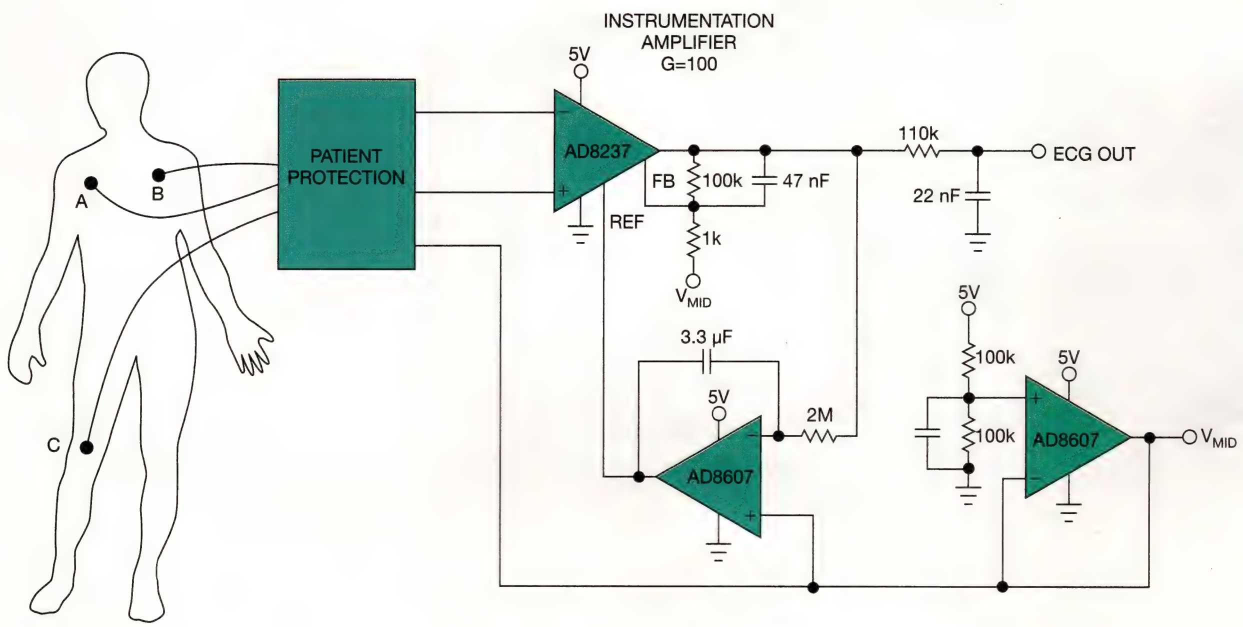


Figure 2 The AD8607 dual micropower instrumentation amplifier is used for integration, buffering, and level shifting in this zero-drift signal-conditioning circuit for an ECG application (courtesy Analog Devices).

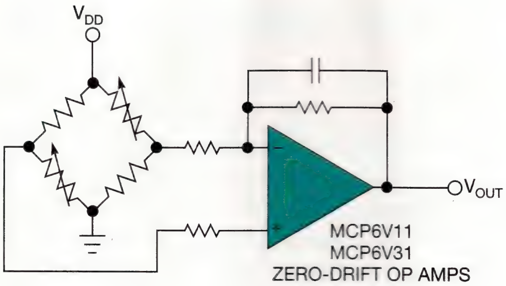


Figure 3 A Wheatstone-bridge sensor conditioned by a zero-drift op amp is shown. Even when using multiple sensors in a Wheatstone-bridge configuration, the total change in output voltage is relatively small; thus, a gain stage is usually required before converting the voltage to a digital signal via an ADC (courtesy Microchip Technology).

to market, their large switching current and layout sensitivity made them difficult to use as well as cost prohibitive. Designers thus limited implementation to select applications in which performance was absolutely critical. Advances in process technology and silicon design have since enhanced the usability of zero-drift amplifiers, proliferating their use across a wide range of applications, including medical devices; industrial flow meters, multimeters, and high-end weight scales; and even gaming devices.

Many sensors, such as strain gauges, RTDs (resistance temperature detectors), and pressure sensors, are commonly arranged in a Wheatstone-bridge configuration (**Figure 3**) because that circuit type offers excellent sensitivity. Even when using multiple sensors in a Wheatstone-bridge configuration, the total change in output voltage is relatively small, typically in the millivolt range. Because of the small signal amplitude, a gain stage is usually required before converting the voltage to a digital signal via an ADC. Zero-drift amplifiers are a good choice for such applications because of the need for high gain and minimum noise, Tretter says.

IA DESIGN CONSIDERATIONS

Adolfo A Garcia, vice president of marketing and applications for Touchstone Semiconductor, notes that when supply voltages are low (<3V) and the available choices for self-contained IAs (instrumentation amplifiers) are limited, designing your own IA is straightforward, so long as the op amp's input and output dc characteristics and circuit topologies are understood. Two very common topologies respectively use two and three op amps to construct the instrumentation amp.

Figure 4 shows the two-op-amp topology. When applying single-supply, rail-to-rail, low-power op amps, primary considerations for their selection,

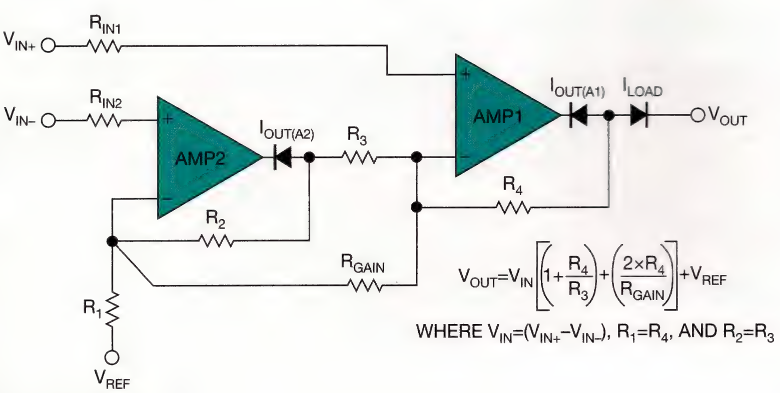


Figure 4 This illustration of a conventional two-op-amp instrumentation amp and its associated output/input voltage-transfer equation shows that two single-supply op amps can be configured into an instrumentation amplifier if certain op-amp parameters are understood and applied correctly (courtesy Touchstone Semiconductor).

WIRELESS SENSOR NETWORKS WRING MORE UTILITY FROM REAL-WORLD DATA

Wireless sensor networks are changing the way information is gathered, increasing the amount and accessibility of data about the physical world. The cost of deploying a wired sensor network is often 10 to 100 times the cost of the sensor. According to Joy Weiss, president of the Dust Networks Product Group at Linear Technology Corp, the real value of WSNs is that you can put a sensor anywhere—not just where power or communications wires are already conveniently located, but wherever you want to take a measurement or add a control point to a system.

Weiss cites some examples of applications enabled by WSNs:

• Vigilent provides intelligent energy management systems, based on its M3 closed-loop control technology, for data centers, telcos, and large commercial buildings. To collect the necessary temperature and humidity data throughout the data center, sensors need to be widely and densely distributed. Retrofitting the data center with communications and power cabling, however, is impractical and cost prohibitive. Vigilent uses wireless connected sensor nodes to address those concerns. In selecting Linear Technology's Dust Networks SmartMesh solution for its product, Vigilent identified as critical success factors the need for low power consumption, high reliability, and robust security.

• Emerson Process Management helps businesses automate their production, processing, and distribution in the chemical, oil and gas, refining, pulp and paper, power, water and wastewater treatment, metals and mining, food and beverage, life sciences, and other industries. Emerson's Smart Wireless products and solutions, based on the IEC 62591 wireless standard and incorporating Linear/Dust's SmartMesh WirelessHART products, extend predictive intelligence into areas previously beyond physical or economic reach.

• Streetline provides smart-parking solutions to cities, garages, airports, universities, and other parking providers (Figure A) and aims to make smart cities a reality through the use of sensor-enabled mobile and Web applications. Streetline needed a wireless networking solution robust enough to function in harsh and dynamic street conditions—one that could be large and dense and that could run for years without a battery change. Streetline's smart-parking solution uses Linear/Dust's SmartMesh technology in a wireless mesh network overlaid on streets in the Hollywood/Los Angeles area. Wireless sensors buried in the street pavement track parking-space availability; the information is then sent wirelessly to smartphone users.

Figure A Streetline Networks' smart-parking management solution uses Linear Technology/Dust Networks' wireless technology in a wireless mesh network overlaid on urban streets. Wireless sensors buried in the pavement gather information on parking-space availability that is sent wirelessly to smartphone users.

depending on the application, include dc parameters such as V_{OS}, TCV_{OS}, $A_{VOL(MIN)}$, I_{OS}, $V_{OH(MIN)}$, and $V_{OL(MAX)}$, and ac parameters such as the amplifier input-referred noise and bandwidth. Regardless of the application, maximizing output dynamic range is key to achieving maximum circuit performance. Single-supply op amps whose output stages offer the widest dynamic range are the best choices, according to Garcia, because amplifier output-stage saturation is to be avoided.

Note the reference-voltage term (V_{REF}) in the circuit's transfer **equation** in **Figure 4**. To avoid output saturation in AMP1, the instrumentation amp's output signal must be measured relative to V_{REF}. In a 3V (or lower) system, one might conclude that, in order for the circuit to exhibit maximum dynamic range and avoid output-stage saturation, simply setting V_{REF} equal to one-half the supply is sufficient. That conclusion is only valid, however, if the selected op amp's $V_{OH(MIN)}$ and $V_{OL(MAX)}$ specifications are symmetric with respect to its supply datum, Garcia observes.

Dispensing with a rigorous nodal circuit analysis of the two-op-amp IA topology involving the differential input signal voltage (V_{IN}), the applied input common-mode voltage (V_{CM}), and the reference voltage, V_{REF} should be designed so as to bias AMP1's output in the middle of its output voltage swing (and not exactly at one-half the supply voltage), as **Equation 1** shows:

$$V_{REF}=\frac{V_{OH(MIN)}+V_{OL(MAX)}}{2}. \qquad (1)$$

Select the desired gain of the IA so as to prevent output-stage saturation. In the case of the two-op-amp IA, the expression derived from the nodal circuit analysis is shown in **Equation 2**:

$$\text{Circuit gain}=\frac{V_{OH(MIN)}+V_{OL(MAX)}}{2\times V_{IN(MAX)}}. \qquad (2)$$

In **Equation 2**, $V_{IN(MAX)}$ is the maximum differential input voltage applied to the IA circuit. If the desired gain is a known circuit parameter, you can rearrange the appropriate terms in the **equation** to determine the maximum input differential voltage that can be applied to the circuit to prevent output-stage saturation.

For the lowest power operation,

resistors used in the circuit should be 100 kΩ or larger, depending on noise and bandwidth design considerations. Also, it is important to point out that an op amp's $V_{OH(MIN)}$ and $V_{OL(MAX)}$ voltage specifications are highly dependent on amplifier output-stage loading, so pay particular attention to load-resistor conditions.

In a real-world example, a TS1002 dual 0.6-µA op amp was chosen to construct a gain-of-10 two-op-amp IA that operates from a 2.5V supply. The TS1002's $V_{OH(MIN)}$ and $V_{OL(MAX)}$ specifications into a 100-kΩ load are 2.498V and 0.001V, respectively. Using **Equation 1**, a V_{REF} equal to (2.498V+0.001V)/2=1.249V offsets the output stage to maximize output dynamic range and avoid output-stage saturation. At a prescribed gain of 10, the maximum differential input voltage that can be applied to avoid output-stage saturation is (2.498V+0.001V)/(2×10), or 125 mV.

You can perform a similar analysis on the three-op-amp IA configuration (**Figure 5**). Again, dispensing with the rigor of a comprehensive nodal circuit analysis of the three-op-amp IA and involving the terms mentioned previously, the results of the two-op-amp IA apply equally well here; that is, for maximum dynamic range, the output reference voltage is set to be in the middle of AMP1 and AMP2's output-voltage swing (**Equation 1**).

The expression for circuit gain is of the same form as for the two-op-amp IA (**Equation 2**). The circuit's output voltage is measured with respect to V_{REF}; V_{REF} is designed to be in the middle of AMP1 and AMP2's output-voltage swing; and the maximum differential input voltage that can be applied to the three-op-amp IA is determined from **Equation 2**.

In another real-world example, designers used a Touchstone Semi TS1004 0.6-µA quad op amp to construct a gain-of-50 three-op-amp IA that operates from a 2.5V supply. From the TS1004's data sheet, its $V_{OH(MIN)}$

and $V_{OL(MAX)}$ specifications into a 100-kΩ load are 2.498V and 0.001V, respectively. Using **Equation 1**, the output stage is offset by a V_{REF} equal to (2.498V+0.001V)/2=1.249V in order to maximize output dynamic range and avoid output-stage saturation. At a prescribed gain of 50, the maximum differential input voltage that can be applied to avoid output-stage saturation is (2.498V+0.001V)/(2×50), or 25 mV.

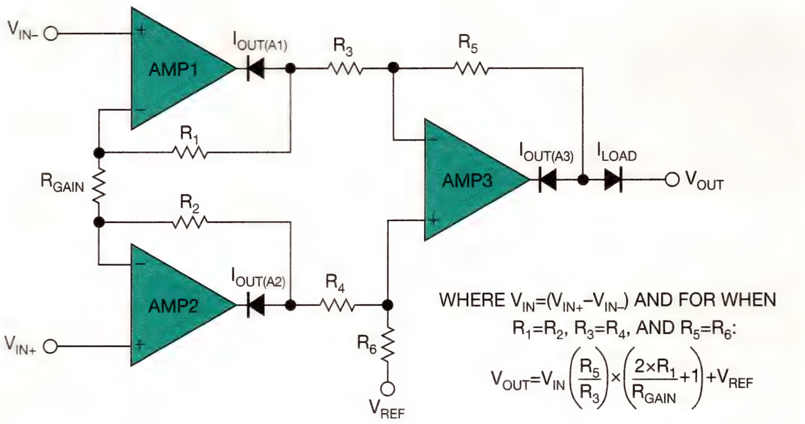


Figure 5 Three single-supply op amps can be configured into an instrumentation amplifier if certain op-amp parameters are understood and applied correctly (courtesy Touchstone Semiconductor).

ENERGY HARVESTING

Tony Armstrong, director of product marketing for power products at Linear Technology Corp, describes powering remote wireless nodes via renewable energy sources that can be harvested efficiently, given the right harvesting, power-management, and battery-charging devices (see **sidebar,** "Wireless sensor networks wring more utility from real-world data"). Renewable energy is providing expanded opportunities for energy conversion and more effective use of existing energy, but it also provides an opportunity for energy-harvesting devices to help power wireless sensor networks, commonly used in building-automation and predictive-maintenance applications.

Armstrong notes that the conventional approach for energy harvesting has been through solar panels and wind generators, but emerging energy-harvesting tools enable the generation of electrical energy from a variety of ambient sources. For instance, thermoelectric generators convert heat to electricity, piezo elements convert mechanical vibration, photovoltaics convert sun-

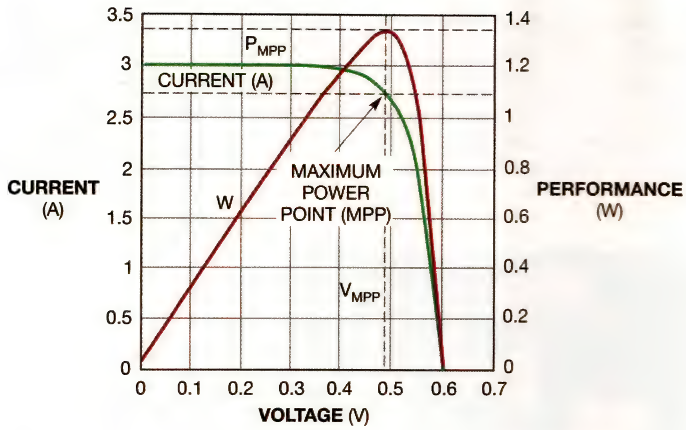


Figure 6 The typical maximum-power-point control point for a single photovoltaic cell is shown. Maximum power output for a given light intensity occurs at the knee of each curve, where the cell transitions from a constant-voltage device to a constant-current device (courtesy Linear Technology).

light (or any photon source), and galvanics convert energy from moisture. This makes it possible to power remote sensors, or to charge a storage device such as a capacitor or thin-film battery, enabling a microprocessor or transmitter to be powered from a remote location without a local power source.

Linear's energy-harvesting products provide enabling solutions (**Table 1**). Specs vary across the line, but the company touts quiescent currents typically less than 6 μA and as low as 450 nA; start-up voltages down to 20 mV; input-voltage capability up to 34V continuous, 40V transient; the ability to handle ac inputs; multiple-output capability and autonomous system power management; autopolarity operation; maximum-power-point control for solar inputs; the ability to harvest energy from as little as a 1°C temperature delta; and compact solution footprints.

Because solar power is variable, nearly all solar-powered devices feature rechargeable batteries. Clearly, the goal is to extract as much solar power as possible to charge these batteries quickly and to maintain their state of charge.

While solar cells are inherently inefficient devices, they do have a point of maximum output power, so operating at this point is an obvious design goal. The problem, Armstrong observes, is that the IV characteristic of maximum output power changes with illumination. A monocrystalline solar cell's output current is proportional to light intensity, whereas its voltage at maximum power output is relatively constant. Maximum

power output for a given light intensity occurs at the knee of each curve, where the cell transitions from a constant-voltage device to a constant-current device (**Figure 6**).

Therefore, a charger design that efficiently extracts power from a solar panel must be able to steer the panel's output voltage to the point of maximum power when illumination levels cannot meet the charger's full power requirements. Linear's LT3652 multichemistry 2A battery charger for solar-power applications uses an input-voltage regulation loop that reduces the charge current if the input voltage falls below a programmed level set by a simple voltage-divider network. When

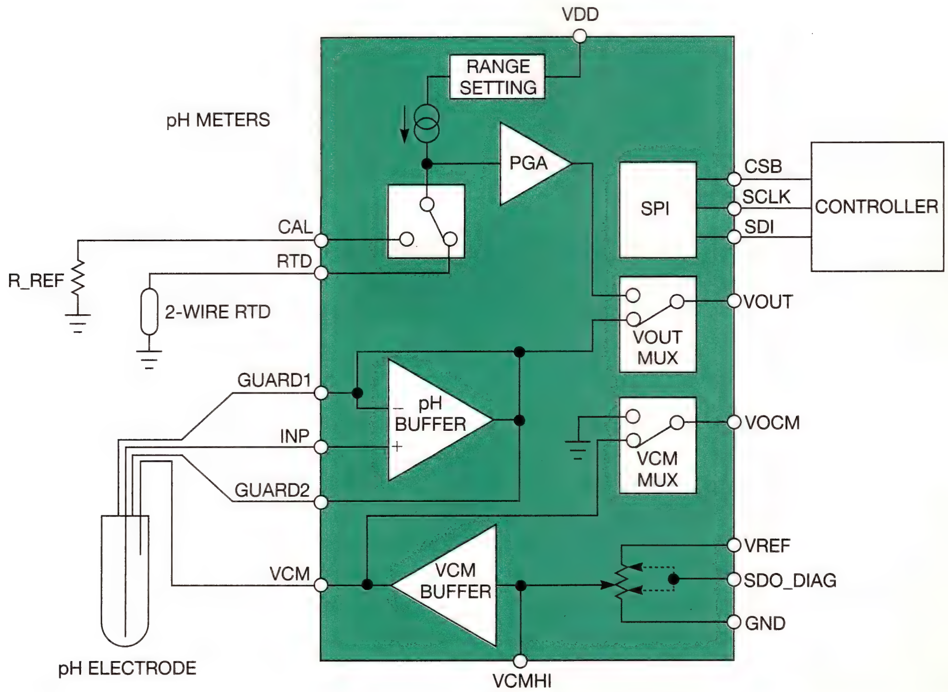


Figure 7 The LMP91200 configurable AFE delivers an integrated pH-sensor AFE circuit that interfaces with all available pH sensors and bridges the gap between sensor and microprocessor (courtesy Texas Instruments).

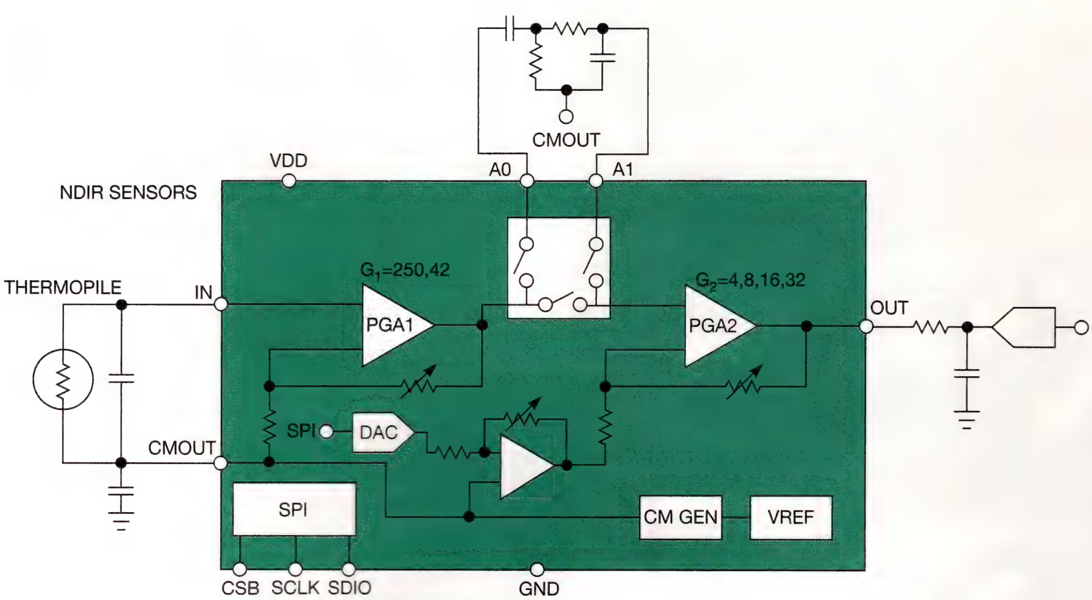


Figure 8 The LMP91050 NDIR gas-sensing AFE supports multiple types of thermopile sensors (courtesy Texas Instruments).

Part number	Description	Energy source
LTC3108	20-mV thermal-energy harvester	Thermal differential
LTC3109	Autopolarity thermal-energy harvester	Thermal differential
LTC3588	Piezo energy harvester	Vibration/strain; piezoelectric
LTC3105	250-mV step-up dc/dc converter with MPPC	Solar photovoltaic
LT3652(HV)	Power-tracking 2A battery charger for solar power	Solar photovoltaic
LTC4070/71	Li-ion shunt battery-charger systems	Solar; piezoelectric

TABLE 1 LINEAR TECHNOLOGY INTEGRATED CIRCUITS FOR RENEWABLE-ENERGY APPS

powered by a solar panel, the input-voltage regulation loop maintains the panel at near peak output.

INTEGRATED AFE APPROACH

Complete sensor solutions need to address sensor drive and output requirements, sample rate, signal-path calibration, performance, sensor diagnostics, and power-consumption needs. Simplifying the cycle and reducing development time can mean a faster time to market and more designs completed per year. Most existing approaches, however, address only a few of those issues and are time-consuming and complicated to develop with discrete components.

Texas Instruments' configurable sensor AFE (analog front-end) ICs and Webench Sensor AFE Designer are part of an integrated hardware and software development platform that lets an engineer select a sensor, design and configure the solution, and download the configuration in minutes. Engineers can evaluate the complete signal-path solution online or on the bench.

Achieving accurate pH measurements in industries such as food processing, water-quality management, and chemical processing involves dealing with design challenges that include extreme temperature variations, high output impedances, offsets, and drifts. TI says its LMP91200 configurable AFE delivers an integrated pH-sensor AFE circuit that interfaces with all available pH sensors and bridges the gap between sensor and microprocessor (**Figure 7**), addressing the design challenges in an integrated, small form factor.

TI's LMP91050 NDIR (nondispersive infrared) gas-sensing AFE, meanwhile, supports multiple thermopile sensors for NDIR sensing, indoor-air-quality monitoring, demand-controlled ventilation, HVAC, alcohol-intake breath analysis, greenhouse-gas monitoring, and Freon detection (**Figure 8**).EDN

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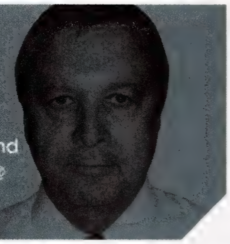

BY PATRICK CARNER • TEXAS INSTRUMENTS

Add LED intelligence to improve light quality, efficiency, and cost

MOVING TO DIGITAL CONTROL LETS OEMs DEPLOY A SINGLE CONTROLLER TO DRIVE A LARGE PORTFOLIO OF END PRODUCTS, OPENING UP DESIGN FLEXIBILITY AND BRINGING NEW LEVELS OF INTELLIGENCE AND DIFFERENTIATION TO LIGHTING INSTALLATIONS.

As the lighting industry makes the transition to LED technology, the need increases for more intelligent controllers and drivers. Efficient operation of LEDs can result in substantial savings to homes and businesses as utility costs rise. Many applications need to produce consistent light quality while supporting advanced control functionality, such as dimming, balancing, and accurate color mixing. Remote connectivity is also becoming a regular requirement for applications in which self-diagnostics can reduce maintenance expenses by limiting the need for technician service calls.

Bringing intelligence into LED lighting applications may require moving from fixed-function LED drivers to microcontroller-based, or programmable, architectures. Specialized power-electronics microcontrollers can further benefit lighting applications with the ability to control the luminaire power supply, in addition to the lighting control and communications, efficiently and cost-effectively. Moving to digital control opens up flexibility and can bring new levels of intelligence and differentiation to lighting products.

ENABLING INTELLIGENT PLATFORMS

The lighting industry has been rapidly evolving to capitalize on the many benefits of LED technology (see **sidebar**, "Benefits of LEDs"). LED lighting applications, however, vary widely in the capabilities they need to support.

Residential applications include light-bulb replacement, accent lighting, and small outdoor lighting. In general, only a few LEDs need to be lit, usually in one or two strings. Given the low-cost pressures of this market, advanced controls are generally not common.

Commercial applications include fluorescent ballasts, light-bulb replacement, and accent lighting. Only a few LEDs need to be lit, usually in one or two strings. Though concerned about cost, this market is also highly energy conscious. Higher-end applications will require remote connectivity and some controller intelligence.

Entertainment applications include high-end display and mood lighting. Full light-intensity control and consistent color quality are essential, as are remote connectivity and support for industry-standard protocols such as DALI (the Digital Addressable Lighting Interface) and DMX512.

Outdoor and infrastructure applications include street lighting and lighting for factories and large office buildings. Equipment typically has a high number of LEDs and must support many strings; high-brightness LEDs are common, as well. These applications require remote connectivity and a high level of controller intelligence.

The simplest LED-based lighting systems use an LED driver, typically a fixed-function device that provides a straightforward and low-cost control method. In general, they offer good power efficiency and do not require software programming. At worst, developers have to make several calculations when selecting a driver or determining which configuration values to use for board-level components.

While straightforward to use, many LED drivers lack sufficient flexibility for more advanced systems. Supporting multiple LED types or string configurations within a given application may call for a different solution. In fact, any change in the system, such as in the number of LEDs in a string or the number of strings in an installation, may result in a need to change the driver. Thus, most of the lighting products an OEM offers will likely require a unique analog driver. For a large portfolio of products, this requirement can increase the number of items an OEM or supplier must stock in inventory, possibly leading to lower economies of scale and higher equipment cost.

An intelligent controller, on the other hand, lets developers create more flexible lighting systems. In a microcontroller-

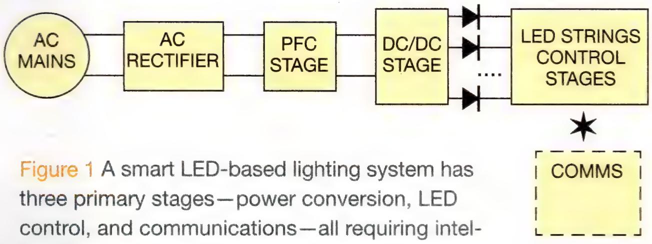

Figure 1 A smart LED-based lighting system has three primary stages—power conversion, LED control, and communications—all requiring intelligent control. With a digital approach to power, controllers can be combined on a single microcontroller to reduce system complexity and cost.

based system, the code can be configured to support varying types of LEDs, unique power-stage requirements, different string lengths, and a variable number of strings without significantly changing the hardware. The system can be designed to autodetect which LEDs it needs to drive. The programmable nature of a microcontroller-based system can even enable advanced dimming and scheduling functions, providing for more advanced lighting-scene control and automated light levels.

The flexibility of digital control lets OEMs design a single controller that can drive a large portfolio of end products. Reusing the controller IP can substantially reduce the design investment. A flexible controller reduces the number of devices that need to be stocked in inventory while lowering overall system cost through greater economies of scale.

INTEGRATION THROUGH DIGITAL CONTROL

The basic architecture of a smart LED-based lighting system comprises three primary stages: power conversion, LED control, and communications (**Figure 1**).

The power-conversion stage delivers the correct voltage and current to the LEDs. It begins with ac/dc rectification, followed by a PFC (power-factor correction) stage and then one or more parallel dc/dc conversion stages. Providing efficient power conversion requires precise and flexible control of these conversion stages.

Each of the primary stages requires an intelligent controller to maintain efficiency and functionality. A fixed-function, analog approach might require separate PFC, dc/dc, LED, and communications controllers. Specialized power-electronics microcontrollers, by contrast, enable high levels of integration that can reduce the component cost of a luminaire power supply. Indeed, with enough performance, power-optimized peripherals, and communications ports, a single microcontroller can provide a central, programmable platform that can harmoniously control all three stages of an intelligent lighting system, handling the power stages, LED lighting control, and communications.

Digital power control also has the potential to enable greater conversion efficiency for dynamic systems. Whereas LEDs offer a major efficiency boost over traditional lighting sources—with a corresponding reduction in operating and energy costs—not all LED-based systems are created equal. Digital power control can enable higher efficiency in the power stages of an LED lighting system when dimming, varying color outputs, or adjusting the light output in any way. Likewise, under fixed lighting conditions, a microcontroller potentially can increase operating efficiency by enabling more advanced power-stage design. Such efficiency gains are highly attractive to end customers and can stand as a key differentiating point between two LED systems that are otherwise equal.

Consider a city looking to replace 2000 streetlights and evaluating two models with a 10% difference in efficiency (**Figure 2**). Note that the input power into the system for the higher-efficiency system is 178W, whereas the lower-efficiency system requires 200W to generate the same, 160W light output. That translates to roughly an additional 10% savings in energy cost per year, or $33,726 for this example, based on the power efficiency of the power supply alone. Those savings are over and above the savings directly attributable to use of an LED-based system.

BENEFITS OF INTELLIGENCE

For many applications, including commercial display and entertainment lighting, the quality of the light produced is important. Quality, in this case, refers to the ability to output consistent light intensity and color. Three primary factors in LED performance are manufacturing variations, temperature, and aging.

LED output can vary significantly from lot to lot; devices within the same product line that use LEDs from different lots may provide different light quality because of variations in manufacturing. Consistency of quality in a single device can be maintained by using LEDs from the same lot, but when that is not possible, devices from different lots that are installed next to each other may produce a noticeable—and unacceptable—difference in the quality of the light they produce. With an intelligent controller, the system can be calibrated to compensate for any variations. Because it is done in software, the calibration process can be streamlined during manufacturing when consistency among products is required.

As the ambient temperature changes, the output of the

BENEFITS OF LEDs

The lighting industry is moving to LED technology across all major segments for the advantages LEDs provide over incandescent, compact fluorescent, and even high-pressure sodium lights. Those advantages include:

- **Higher efficiency. LEDs' high lumens/watt performance provides substantial energy savings over traditional lighting sources.**
- **Lower maintenance. LEDs have a lifetime on the order of 50,000 hours and therefore require less frequent replacement and maintenance.**
- **Directional lighting. Less light output is required to light an area when the light source can be directed. There is also less light runoff, and therefore lower light "pollution," with LEDs than with other sources.**
- **Resilience to vibration. This is important for applications such as street lighting, where external forces can affect a light's operating life.**
- **Safer technology. LEDs do not contain mercury and are environmentally safer than some other lighting technologies.**
- **Intelligent control. LED light systems can support advanced features to improve efficiency and provide more optimized lighting. Features range from automatic dimming to matching available ambient light and adaptive time-of-day operation to maximize energy cost savings.**
- **Fast operation. LEDs offer quick on/off switching and have a low startup time.**

LED will change, as well. To compensate, the system needs to be able to sense the environmental temperature with a sensor. The microcontroller will need to read the sensor and adjust the LED drive accordingly to correct the color and intensity dynamically. Because the temperature needs to be checked only periodically, this function has a low overhead. It also lets the system monitor its own safe operation; if the temperature of the LED exceeds a specific threshold, the lighting controller can reduce the intensity or shut down the string while remotely notifying an operator of the issue. Extreme heat can prematurely age an LED and degrade its light output. Ensuring that an LED does not exceed a certain temperature will prolong its usable life.

LED aging also affects quality, causing color-profile variations. For example, a red LED ages faster than a blue one, and the color produced by a particular power output or PWM frequency will shift over time. An intelligent controller can account for aging and correct the color profile to maintain consistent lighting throughout the life of an LED system.

The same technology that manages quality can improve safety and efficiency. Lighting can be adjusted to match available ambient light; on a stormy day, for example, streetlights can be turned on early at a partial setting, or during periods when there is ample ambient light, the lighting can be adjusted down to consume less power. Sensors at traffic lights or specific streetlights could monitor late-night traffic conditions and raise the street lighting level if traffic becomes extraordinarily active.

In a warehouse, workers may utilize different spaces sporadically. Using occupancy sensors, it becomes possible to light only those sections that are currently in use. If only 50% of the floor is in use at any time, then the rest of the lights can be turned off, for a 50% energy savings.

Again, consider the streetlight example from **Figure 2**. During late-night hours, many streetlights can be run at less than their full illumination because of reduced traffic loads. If motion sensors are in use with a communications network, lights can be dynamically turned on and off to meet actual traffic needs. For the higher-efficiency, 178W-input system shown in **Figure 2**, shutting down the lights 25% of the time results in a corresponding 25% energy savings, or $68,218 annually, as this series of **equations** shows:

$$1{,}819{,}160 \text{ kWhr/year} \times 75\%\text{/night operating time} = 1{,}364{,}370 \text{ kWhr/year}$$

$$1{,}364{,}370 \text{ kWhr/year} \times \$0.15\text{/kWhr} = \$204{,}656 \text{ annual cost}$$

$$\$272{,}874 \text{ initial annual cost} - \$204{,}656 \text{ revised annual cost} = \$68{,}218 \text{ annual savings}$$

Combining the savings from power-supply efficiency with the savings from intelligent operation yields a substantial total savings per year of $101,944, or approximately 33%, for the system.

REMOTE CONNECTIVITY

Remote connectivity is a key capability for intelligent lighting systems. Intelligent devices can automatically manage some aspects of their operation to improve efficiency and quality. Unless the equipment can communicate with a centralized controller, however, such intelligence has to be preprogrammed and can maximize the efficiency of only that single piece of equipment.

By networking the various components in a lighting system, developers can coordinate the operation of equipment across an entire installation. Doing so enables a whole new class of functionality, including remote dimming, remote shutoff, and emergency control. Operators can adjust the lighting intensity of an entire installation of lights from a centralized location rather than individually adjust each light.

To achieve the most functionality, each component must be able not only to receive information but also to pass it

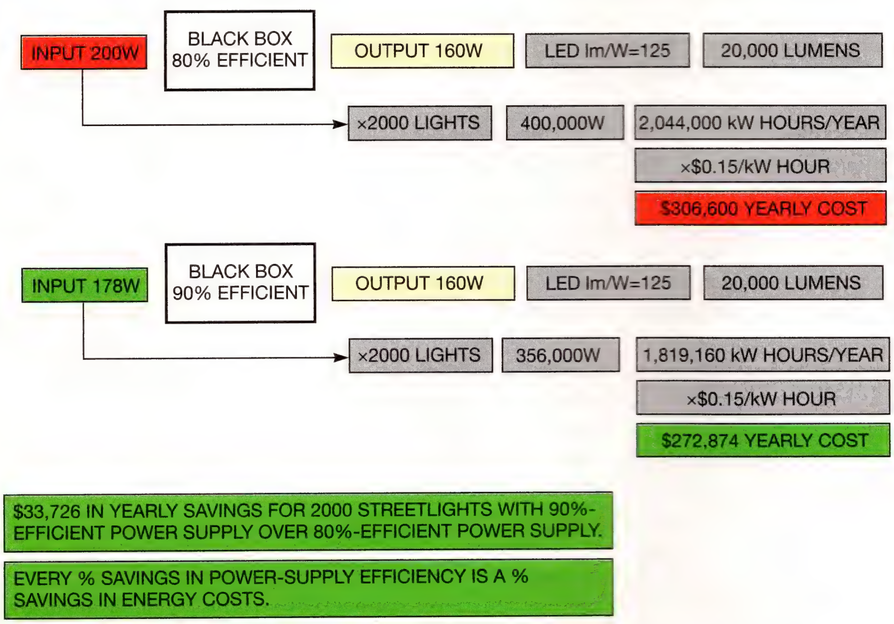

Figure 2 Compared with analog systems, digital control of power enables greater conversion efficiency over and above the savings gained from using LED technology. Here, a 10% difference in efficiency translates to roughly an additional 10% energy cost savings per year, or $33,726 for this example.

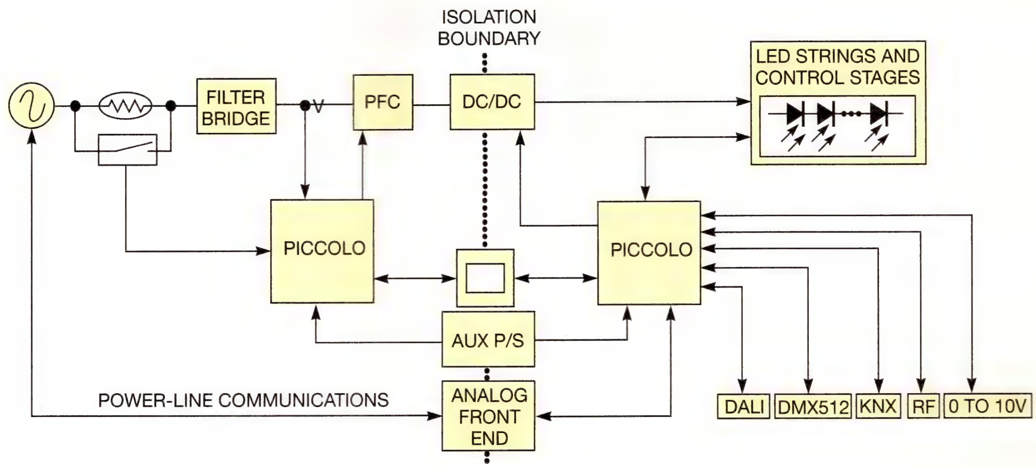

Figure 3 In systems requiring the use of an isolation boundary between high and low voltages, such as the one shown here, it may be easier to use two microcontrollers, linked via I²C or SPI, for communications. If the design is nonisolated, then implementing PFC and dc/dc conversion on the same MCU is straightforward.

back up to operators. In this way, lights can perform simple self-diagnostics to identify such issues as whether an LED has burned out or is performing below a minimum quality threshold and alert operators to initiate any necessary maintenance. Rather than send out technicians on a regular maintenance schedule to ensure equipment is operating as expected, an operator can check it remotely and send out technicians only when an issue arises that requires their attention. Such remote monitoring, coupled with the extended operating life of LEDs, can result in significant maintenance cost savings as well as increased operational safety, because failures can be identified immediately.

Remote control enables other advanced features that substantially affect operating efficiency and cost, allowing dynamic control of lights as well as networking of multiple lighting installations to a single point of control at a location that may be a great distance from the actual installations. For example, streetlights may need to be adjusted for daylight saving time. Rather than send a technician out to each control box, a lighting-system operator can remotely correct the schedule of all lights in the system. Operators also can easily accommodate unexpected changes in schedules, such as the need to light the roads after a late-ending sports event or keep the lights on in a factory during the rush season. Remote control can also foster safety by enabling direct control of lights during emergency conditions.

One of the more beneficial features of intelligent lighting for commercial and industrial installations is the ability to track power consumption accurately. Cities, for example, traditionally pay a fixed rate to operate streetlights. With an intelligent lighting controller, municipal operators can track the actual power consumed and send the data to a centralized location to ensure that the city does not pay for more power than its citizens actually use.

Data logging of actual usage lets operators refine their planning of operating costs, maintenance resources, and future investments. It also enables more advanced predictive diagnostics. Dramatic spikes in energy consumption or in the number of replacement bulbs required can alert operators to underlying issues that, if caught early, can be addressed before they drive up operating and maintenance costs.

Connectivity is also essential for many lighting systems, especially entertainment applications. There are many established communications standards in this market space—including DALI, DMX512, and KNX—and equipment that can support those protocols can have a competitive edge.

POWER-LINE COMMUNICATIONS

PLC (power-line communications)—which lets engineers run network equipment over the same lines used to power equipment, rather than install a separate cable to serve as the communication link—is an important technology for lighting applications. For applications not requiring the full PLC feature set, PLC-Lite is a flexible alternative that offers simplicity and reduced-protocol overhead in exchange for a lower data rate. Developers can implement PLC-Lite at a substantially lower cost per link than is possible with more complex varieties of PLC, such as G3 or PRIME (Powerline Intelligent Metering Evolution).

Because it isn't a fixed standard, developers can exploit the flexibility of PLC-Lite to optimize an implementation to specific channel characteristics in order to improve link robustness in environments where interference on the line requires exceptional handling. PLC-Lite is well suited for applications in which a low-cost but robust communications channel is needed, such as simple light bulbs or wall switches within a home network.

Developers can also connect devices wirelessly using radio-frequency technology. With a modular architecture, devices can use whichever connectivity technology best meets customer needs. Whether the link is PLC- or Wi-Fi-based, data is passed to the microcontroller over a standard I²C or SPI port.

THE INTEGRATED ADVANTAGE

To keep system cost down, developers need a microcontroller that provides sufficient processing capacity to implement

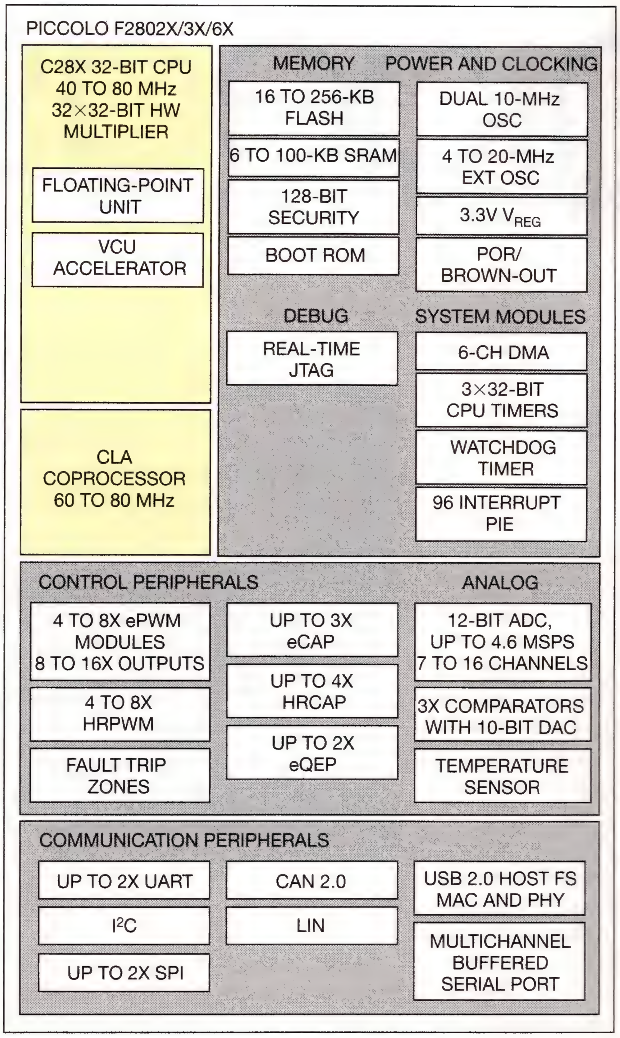

Figure 4 TI's Piccolo microcontroller platform offers a high-performance, highly integrated architecture designed for digital power control that is flexible in its support of a variety of power topologies.

the power stage, LED control, sensor input, and remote connectivity with a single microcontroller. In general, a single-chip design that integrates all of a system's controllers is less expensive than one that requires multiple MCUs.

In some lighting systems, however, the presence of high and low voltages often requires the use of an isolation boundary between PFC and dc/dc conversion (**Figure 3**). In such cases, it may be easier to use two microcontrollers that communicate using an I²C or SPI interface across the isolation boundary. If the design is nonisolated, then it is relatively straightforward to implement PFC and dc/dc conversion functionality on the same microcontroller.

When using a single microcontroller for an LED design, you'd want a high-performance architecture ideal for a wide range of applications, preferably one designed for digital power control with flexibility to support a variety of power topologies. Microcontrollers that integrate the following capabilities on-chip are preferable:

- PWM generation with high-resolution and duty-cycle control, as well as high-resolution deadband, to enable more efficient, higher-performing control of power stages. Advanced PWMs offer the capability to generate very precise color outputs and dimming levels; for example, with 16 PWM outputs, a microcontroller can individually control up to 16 separate LED strings.
- Analog-to-digital converters that provide sampling and conversion speeds up to 4.6M samples/sec. Combined with the PWM, the A/D modules let engineers create a tight feedback loop to respond quickly to changing system and environmental operating conditions.
- Built-in fault-protection mechanisms to handle overcurrent and overvoltage conditions. PWM fault trip zones let the system bypass the CPU and quickly override PWM signals with a preprogrammed state in the unexpected system conditions to avert system damage.
- I²C, SPI, UART, USB, and CAN peripherals with production-ready firmware drivers to meet the connectivity needs of most LED applications.

One example of an integrated microcontroller for LED lighting designs is Texas Instruments' C2000 Piccolo platform (**Figure 4**). The 32-bit TMS320C28x core offers digital-signal-processing performance in a microcontroller device with optimized math operations, an interrupt-driven architecture for real-time control, and programmable flexibility to respond to changing events. TI's integrated CLA (Control Law Accelerator), a separate processing core, enables dual-core operation without the added cost or overhead of a second MCU. Able to run independently of the C28x DSP core, the CLA is designed to provide efficient parallel processing.

By partitioning functions of a lighting system between the C28x core and CLA core, Piccolo microcontrollers can implement a complete intelligent LED controller in a single chip. For instance, the CLA could be used to run PLC algorithms while the C28x core focuses on digital power conversion and LED string control. For applications that require more advanced or higher-bandwidth PLC, an integrated Viterbi complex math unit (VCU) is available on Piccolo F2806x microcontrollers; the VCU is specifically tuned for PLC algorithms and can accelerate PLC processing by up to seven times compared with devices without a VCU.

Many companies offer development hardware and software to assist engineers in evaluating and designing LED-based lighting applications ranging from low-voltage, auxiliary-powered systems to high-voltage, full ac-mains-powered systems with remote connectivity. The TMDSIACLEDCOMKIT ac LED lighting and communications developer's kit provides a complete platform for accelerating the design of ac-mains-powered, intelligent lighting products with high operating efficiency (approximately 90%) and full support for remote connectivity and lighting communication protocols.EDN

AUTHOR'S BIOGRAPHY

Patrick Carner is the C2000 microcontrollers and lighting applications marketing manager at Texas Instruments, where he is responsible for product definition and positioning, customer design engagements, business development, and customer support. Carner received a bachelor of science degree in EECS from the University of California at Berkeley.

Low-distortion discrete buffer amplifier handles bipolar signals

Peter Demchenko, Vilnius, Lithuania

Sometimes, the need arises for a low-distortion buffer amplifier capable of handling bipolar signals. You can use an op amp or integrated buffer for these applications, but for more flexibility, a discrete design may prove useful. Applications include buffering the input of an ADC or the output of a DAC, or an audio line driver.

The buffer in **Figure 1** provides unity gain, low output impedance, and low distortion. It uses two emitter followers configured as symmetrical class-A amplifiers; current sources replace the usual emitter resistors (**Figure 2**). To obtain the best results, you should use complementary transistors (Q_1 and Q_2) with closely matched dc gain (beta).

This topology has advantages over a conventional emitter follower. It produces a lower level of even-order harmonics and lower noise, it can provide low I_{BIAS} and V_{BIAS} at the input and low offset voltage at the output, and it exhibits a high power-supply rejection ratio. The circuit doesn't require temperature compensation and is dc stable. Like conventional voltage followers, it has local feedback only. This setup is advantageous in some applications where a long feedback loop can introduce additional distortions or instability.

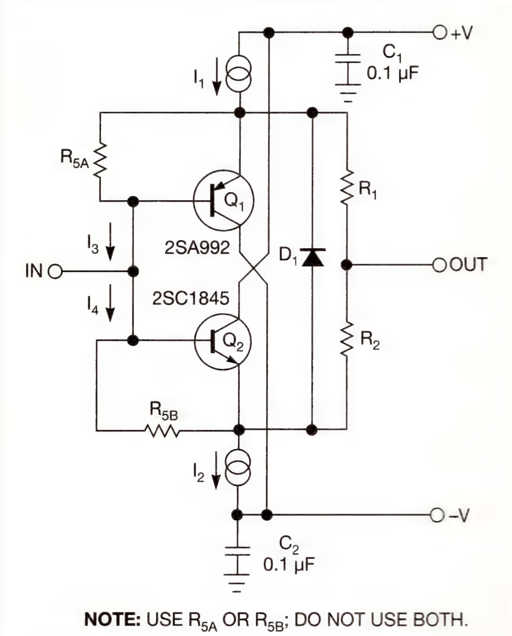

Figure 1 The buffer provides unity gain, low output impedance, and low distortion; see Figure 2 for details of the current sources in the transistors' emitters.

Resistors R_1 and R_2 sum the two outputs. For even harmonics cancellation, their values should be matched. Preferred devices—metal film/foil, for example—should be stable and linear, and should produce low noise.

The voltage drop across R_1 is equal to the base-emitter voltage, V_{BE}, of Q_1; thus, $R_1=K\times V_{BE}/I_1$, where K is in the range of 3 to 20.

R_2 is set equal to R_1. The same resistors also provide stability when driving a capacitive load, so the value of K depends on this capacitance. For the ac-equivalent circuit, these resistors appear to be connected in parallel, thus providing low output impedance. Diode D_1 protects the emitter junctions of both transistors from excess input voltages. When the buffer is used as an output stage, you can eliminate D_1.

The dc gains of the two transistors usually are not perfectly matched, resulting in a slight output offset voltage. To compensate, note the addition of base-emitter resistors R_{5A} and R_{5B} in **Figure 1**. To reduce the output offset voltage to almost zero, you can add R_{5A} or R_{5B}, not both. As an example, assume that $\beta_2>\beta_1$; R_{5B} is then used at Q_2. If Q_1 has the higher beta, R_{5A} would be used at Q_1. You can estimate R_5's value from the following **equation**: $R_5=\beta_1\times\beta_2\times V_{BE}/(I_1\times(\beta_2-\beta_1))$, where β_1 and β_2 refer to the beta of Q_1 and Q_2.

When the output is balanced with the help of R_5, input bias current is also minimized because the currents I_3 and I_4 cancel out each other.

The circuit shown in **Figure 3** is a version of the circuit shown in **Figure 1** that will automatically servo the output to a voltage close to zero. The integrator, IC_1, averages the output voltage but does not pass the ac signal, because it is acting like a high-pass filter; its corner frequency, f_C, can be calculated from this **equation**: $f_C=1/(2\times\pi\times R_3\times C_3)$. In this circuit, f_C is approximately 1.6 Hz.

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LINEAR TECHNOLOGY

DESIGN NOTES

60V, Synchronous Step-Down High Current LED Driver

Design Note 508

Hua (Walker) Bai

Introduction

The meaning of the term "high power LED" is rapidly evolving. Although a 350mA LED could easily earn the stamp of "high power" a few years ago, it could not hold a candle to the 20A LED or the 40A laser diodes of today. High power LEDs are now used in DLP projectors, surgical equipment, stage lighting, automotive lighting and other applications traditionally served by high intensity bulbs. To meet the light output requirements of these applications, high power LEDs are often used in series. The problem is that several series-connected LEDs require a high voltage LED driver circuit. LED driver design is further complicated by applications that require fast LED current response to PWM dimming signals.

The LT®3763 is a 60V synchronous, step-down DC/DC controller designed to accurately regulate LED current at up to 20A with fast PWM dimming. It is a higher voltage version of its predecessor, the LT3743. It can be applied in a number of other applications thanks to its three additional regulation loops:

1) An output voltage regulation loop enables constant output voltage operation. This can be used to provide open LED protection or charging termination for a battery charger.

2) A second current regulation loop can be used to set an input current limit.

3) An input voltage regulation loop can be used for maximum power tracking (MPPT) in solar-powered applications.

48V Input to 35V Output, 10A LED Driver Optimized for Efficiency

Figure 1 shows a design that delivers 350W output power to drive up to seven LEDs in series from a 48V source. At this high power level, dissipated power is a major concern, so high efficiency is critical. Each 1% of efficiency improvement reduces the loss by 3.5W—significant if the total power loss budget is less than 7W. This circuit is optimized to operate with 98.2% efficiency at full load—Figure 2 shows the efficiency reaching 98% when LED current is above 3A and peaking at 98.4% at ~6A.

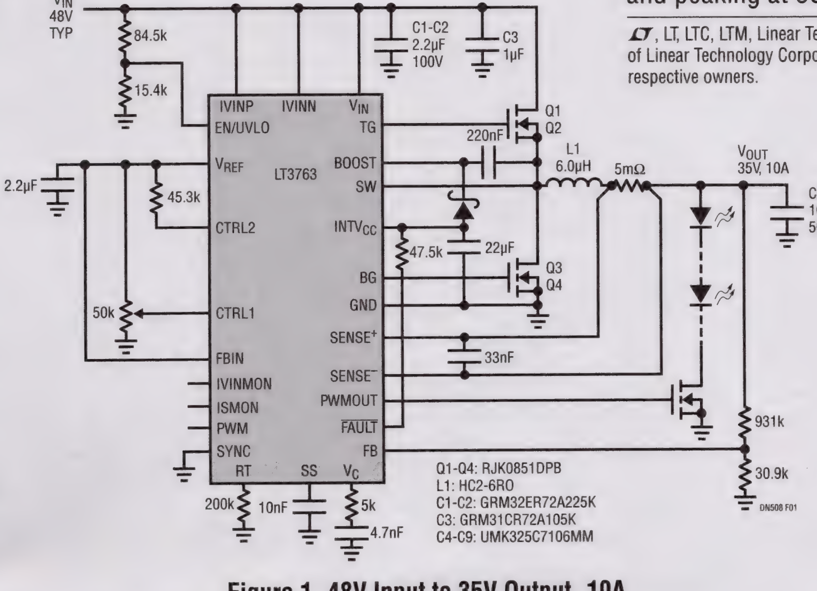

Figure 1. 48V Input to 35V Output, 10A

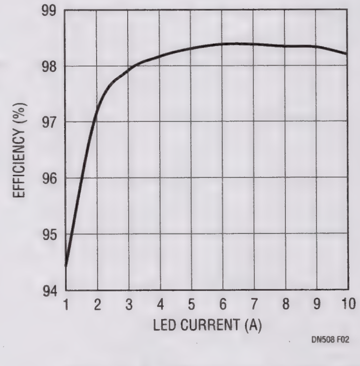

Figure 2. Efficiency of the 48V Input to 35V Output Circuit

At high voltage, the switching losses of the MOSFETs and the inductor outweigh conduction losses. The switching frequency is set to 200kHz to minimize switching losses while maintaining small solution size. Running at full load, this circuit's hot spot occurs at the top MOSFETs, which settles at less than 50°C temperature rise—a very comfortable range for the MOSFETs.

36V Input to 20V Output, 10A LED Driver with Fastest PWM Dimming

PWM LED dimming is the standard dimming method for high power, high performance lighting applications. Fast LED current response to a PWM signal is important in image-producing applications, such as DLP projectors. Figure 3 shows the LT3763 in an application optimized for fast LED PWM dimming.

To achieve fast LED current response to the PWM signal, the LT3763 includes many innovative features. For a given input voltage, the smaller the inductance, the faster the inductor current ramps up, which translates to faster LED current response. This circuit takes only a few microseconds to reach full LED current from zero current when a PWM dimming signal is turned on. Figure 4 shows the performance in the PWM dimming application. Efficiency is 97% at full load.

Solar-Powered Battery Charger

The LT3763 can also regulate its input voltage by adjusting its output current. This is useful for applications that must track peak input power such as in a solar-powered battery charger.

Every solar panel has a point of maximum output power that depends on panel illumination, voltage and output current of the panel. In general, peak power is achieved by maintaining the panel voltage in a small range by reducing output current when needed to prevent the panel voltage from moving out of this range. This is called maximum power point tracking (MPPT).

The LT3763's input voltage regulation loop keeps the panel voltage in maximum power point range by adjusting output current. The constant current, constant voltage (CCCV) operation and C/10 function make the part a natural fit for battery charger applications.

Conclusion

The LT3763 is a 60V, synchronous, high current step-down LED driver controller that can be used to drive the latest high power LEDs, with fast PWM dimming response if needed. The LT3763 is not limited to LED driver applications, due to its three additional voltage and current regulation loops and a number of other powerful features.

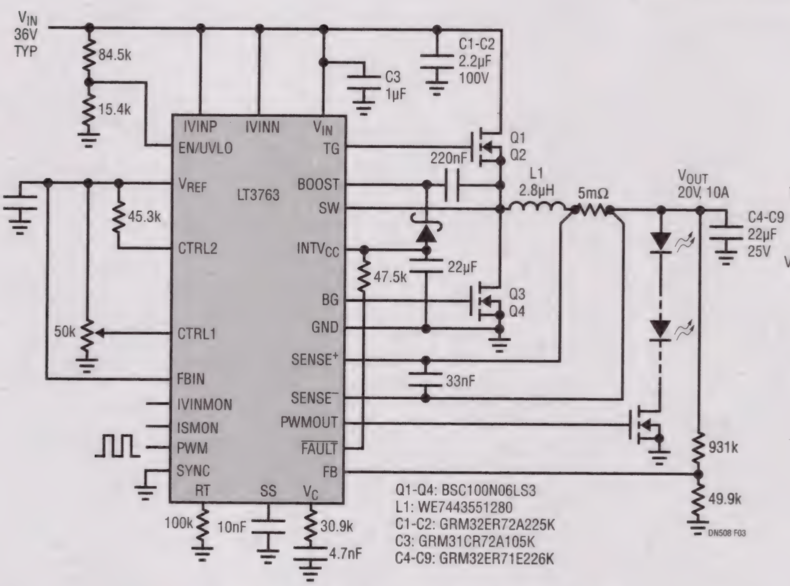

Figure 3. 36V Input to 20V Output, 10A

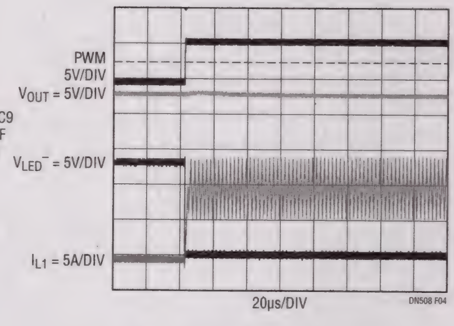

Figure 4. PWM Dimming Performance of Figure 3 Circuit

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The output of the integrator drives an optocoupler that uses a photoresistive element on the output side. This resistor replaces the upper and lower R_5 resistors. The circuit in **Figure 3** provides an output offset voltage of almost zero even with an input offset voltage applied, as long as it isn't too high. The op amp, IC_1, should have low noise, low bias current, and low offset voltage; also, resistor R_3 and capacitor C_3 should be high-quality, stable devices.

One of the optocouplers in **Figure 3** will always be inactive, but unless you know in advance which of the two beta values is higher, you won't know which optocoupler is not active. High-quality photoresistor optocouplers can be rather expensive, so if you know the transistors' beta values, you can replace one device with a diode, D_2, as shown in **Figure 4**. In this version, $\beta_2>\beta_1$, so the photoresistor shunts Q_2. R_4 also can be omitted if the optocouplers' LEDs can tolerate the maximum output current from the integrator.

Incidentally, an optocoupler with an incandescent (filament type) lamp can be used; in this case, the integrator is not needed, because the filament acts as an integrator. Change the integration capacitor to 1M and the input resistor value to 1k (**Figure 5**). The last circuit has low dc gain (compared with the integrator), so the output dc offset can be rather high—tens of millivolts. Diode D_2 prevents possible "latching" of the circuit. EDN

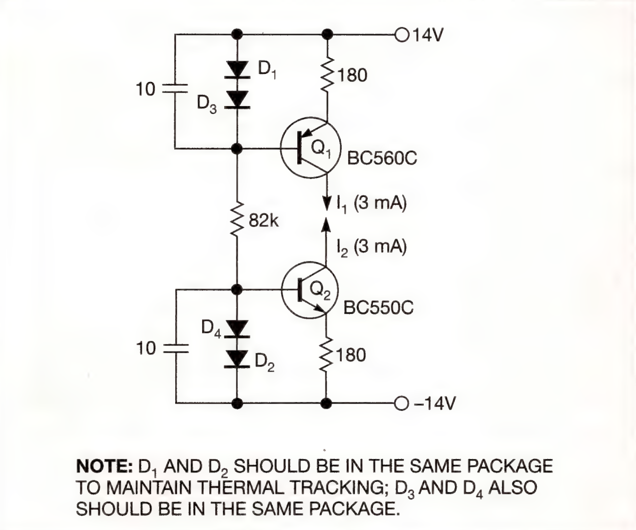


Figure 2 Shown are details of the current sources used in the emitters of the transistors in Figure 1.

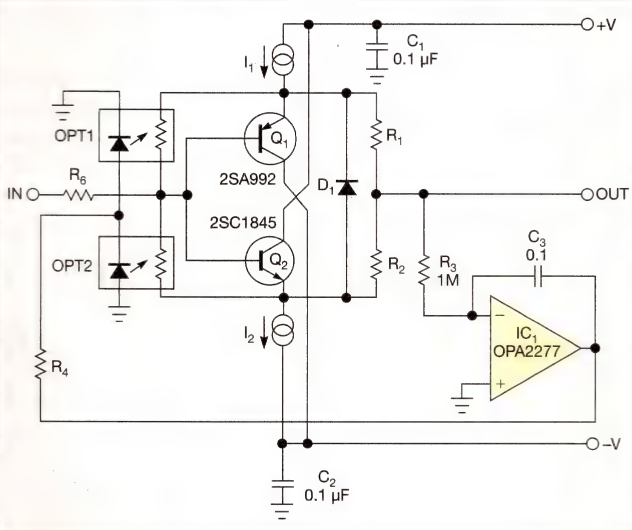


Figure 3 This circuit is a version of the circuit shown in Figure 1 that will automatically servo the output to a voltage close to zero.

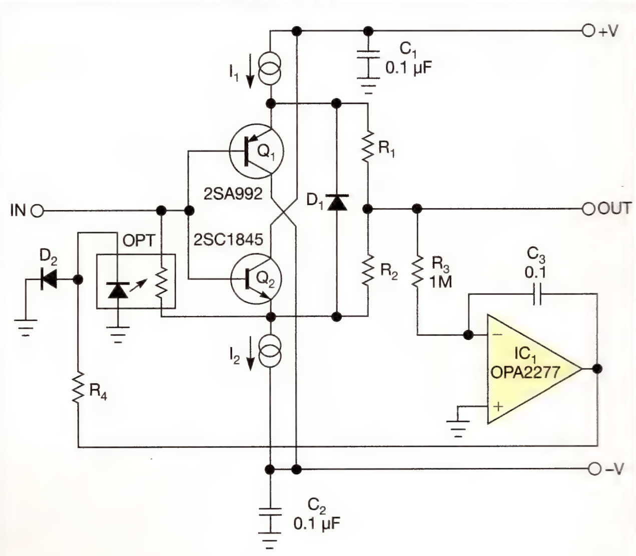


Figure 4 If you know which beta value is higher, you can replace one device with a diode, D_2.

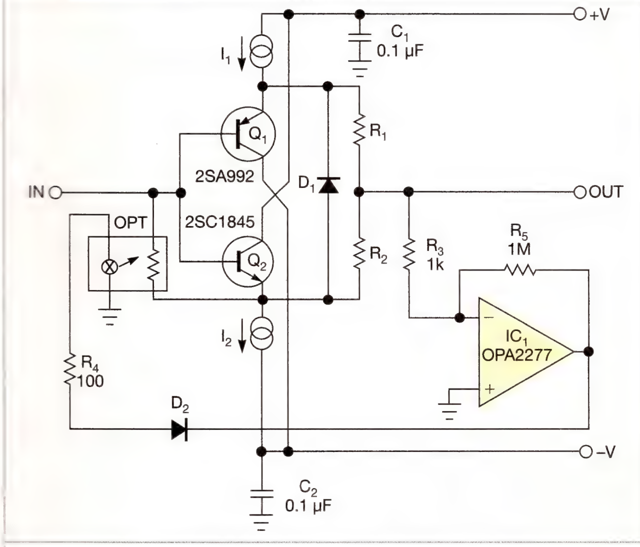


Figure 5 An optocoupler with an incandescent lamp can be used; in this case, the integrator is not needed, because the filament acts as an integrator.

Single-ended-to-differential converter has resistor-programmable gain

Sandro Herrera and Moshe Gerstenhaber, Analog Devices, Wilmington, MA

Many applications—such as driving modern ADCs, transmitting signals over twisted-pair cables, and conditioning high-fidelity audio signals—require differential signaling to achieve higher signal-to-noise ratios, increased common-mode noise immunity, and lower second-harmonic distortion. This requirement presents a need for a circuit block that can convert single-ended signals to differential signals; that is, a single-ended-to-differential converter.

For many applications, an AD8476 precision, low-power, fully differential amplifier with integrated precision resistors is more than adequate to perform the single-ended-to-differential conversion function. For applications that require improved performance, however, an OP1177 precision op amp can be cascaded with the AD8476, as shown in **Figure 1**. This single-ended-to-differential converter has high input impedance; 2-nA (max) input bias current; 60-μV (max) offset voltage, referred to the input; and 0.7-μV/°C (max) offset voltage drift, referred to the input.

The presented circuit is a two-amplifier feedback arrangement in which the op amp determines the circuit's precision and noise performance, while the differential amplifier performs the single-ended-to-differential conversion. This feedback arrangement suppresses the errors of the AD8476, including noise, distortion, offset, and offset drift, by placing the AD8476 inside the op amp's feedback loop, with the op amp's large open-loop gain preceding it. In essence, the arrangement attenuates the errors of the AD8476 by the open-loop gain of the op amp when referred to the input.

External resistors R_F and R_G set the gain of the single-ended-to-differential converter in **Figure 1** such that

$$\text{GAIN}=\frac{V_{OUT,\,DIFF}}{V_{IN}}=2\left(1+\frac{R_F}{R_G}\right).$$

A minimum gain of two can be achieved by replacing R_F with a short and R_G with an open.

As with any feedback connection, care must be taken to ensure the system is stable. The cascade of the OP1177 and the AD8476 forms a composite differential-out op amp whose open-loop gain over frequency is the product of the OP1177's open-loop gain and the AD8476's closed-loop gain. The closed-loop bandwidth of the AD8476, therefore, adds a pole to the open-loop gain of the OP1177. To ensure stability, the bandwidth of the AD8476 should be higher than the unity-gain frequency of the OP1177. This requirement is relaxed when the circuit is in a closed-loop gain greater than two, because the resistor feedback network effectively reduces the unity-gain frequency of the OP1177 by a factor of $R_G/(R_G+R_F)$. The AD8476 has a bandwidth of 5 MHz, and the OP1177 has a unity-gain frequency of 1 MHz, so the circuit shown does not exhibit stability issues at any gain.

When using an op amp with a unity-gain frequency that is much larger than the differential amplifier's bandwidth, you can insert a bandwidth-limiting capacitor, C_F, as shown in **Figure 1**. Capacitor C_F forms an integrator with the feedback resistor R_F such that the bandwidth of the overall circuit is given by

$$\text{BANDWIDTH}=\frac{1}{2}\left(\frac{1}{2\pi R_F C_F}\right).$$

The factor of one-half in the bandwidth **equation** is due to the circuit's output being fed back single-endedly rather than differentially. As a result, the circuit's feedback factor and bandwidth are reduced by two.

If this reduced bandwidth is lower than the closed-loop bandwidth of the differential amplifier, the circuit will be stable. This bandwidth-limiting technique also can be employed with a gain of two by making R_G an open circuit. **EDN**

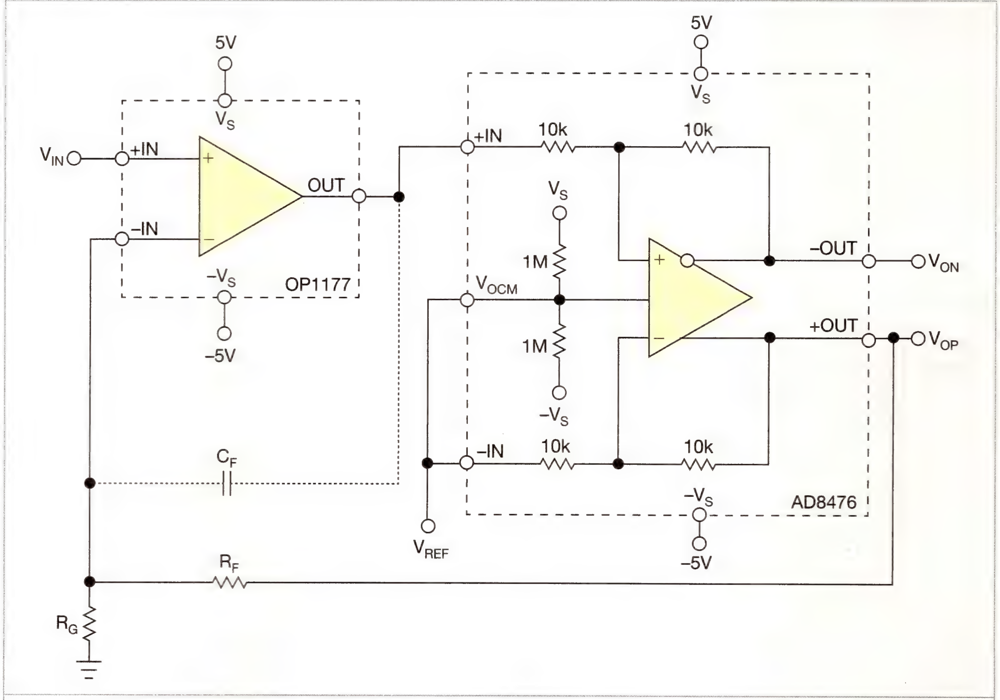
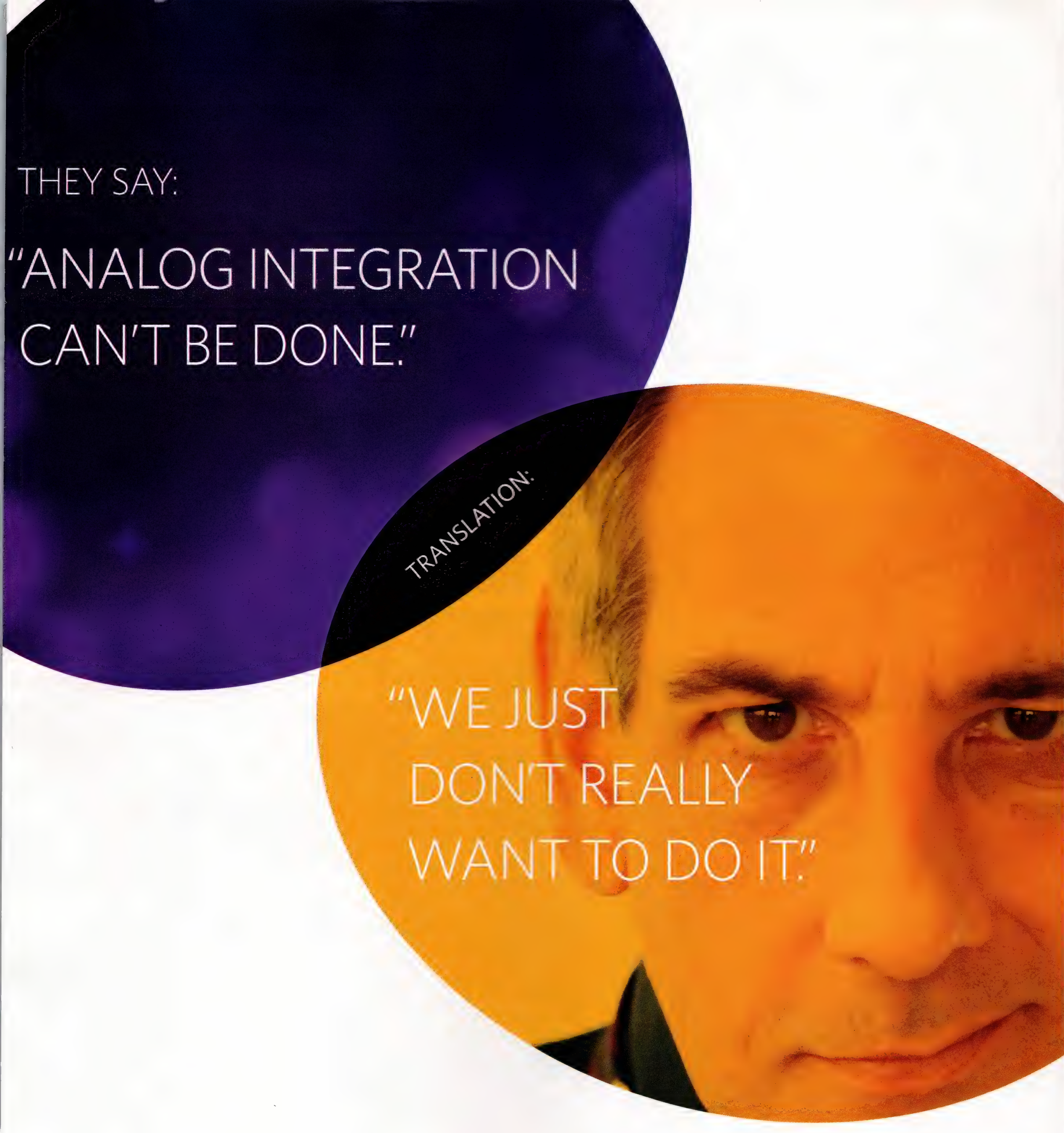


Figure 1 You set the gain of this single-ended-to-differential converter by adjusting the ratio of R_F to R_G.


THEY SAY:
"ANALOG INTEGRATION CAN'T BE DONE."
TRANSLATION:
"WE JUST DON'T REALLY WANT TO DO IT."

Generate boost rails in a bridge-rectifier circuit

Horst Koelzow, Calgary, Alberta

Many single-voltage power supplies consist of a transformer, a rectifier, and a filter capacitor, as shown in **Figure 1**. This circuit is relatively inexpensive and easy to build but supplies only a single voltage. Circuits employing op amps, data converters, and other analog circuit blocks often require additional voltages to operate. These extra voltages can be either higher than the main supply voltage or negative. In such cases, additional transformer windings and rectifiers are added. This approach is practical if all supply voltages have similar power requirements, but analog bias voltages usually have relatively low power requirements that may not justify the

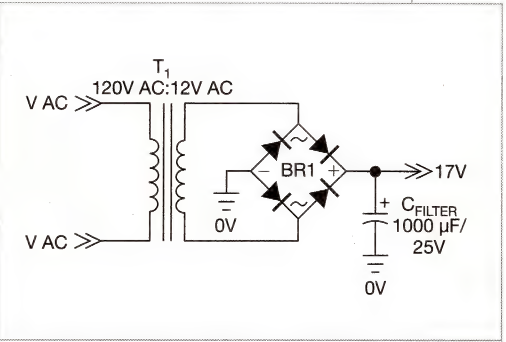


Figure 1 Many single-voltage power supplies comprise a transformer, rectifier, and filter capacitor.

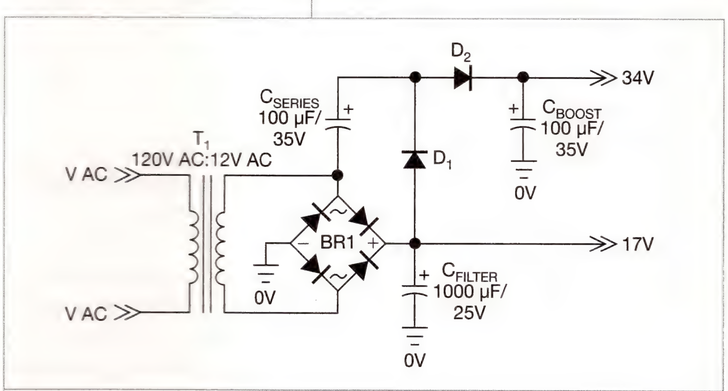


Figure 2 With some modification, a voltage doubler can be implemented.

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overhead of additional transformer windings, rectifiers, and filters. Note that for voltages *lower* than the main supply voltage, a series voltage regulator or resistor divider generally is sufficient.

Because the bridge input and output do not share a common reference, standard negative peak detectors and voltage multiplier stages cannot be used. The bridge ac inputs, however, do have the ability to sink and source current with reference to the bridge-rectifier outputs. With some modification, a voltage doubler can be implemented (**Figure 2**).

Using the same structure and referencing it to the 0V rail can produce a negative bias. Note that positive and negative boost rails can operate at the same time. **Figure 3** shows a modified version of the circuit with both positive and negative boost voltages added.

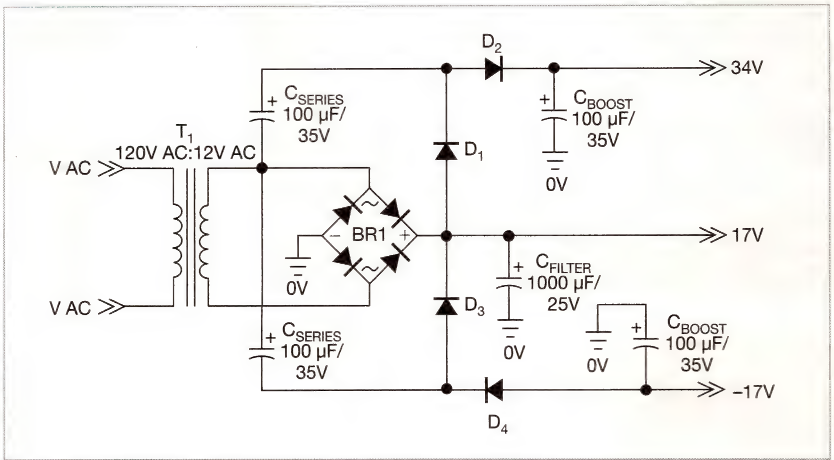

Figure 3 A modified version of the circuit has both positive and negative boost voltages added.

A supply using a 12V transformer has been used as an example, but the technique can be used for other voltages, as well. Note that series and boost capacitors have a higher voltage rating than do filter capacitors. Filter capacitors see only the peak of the rectified ac waveform, while series and boost capacitors see about two times the peak value (less extra diode drops). Capacitance values of series and boost caps vary with output power, and there is no inherent need for series and boost capacitors to be the same value.

In theory, negative and boost rails are capable of power levels similar to those of the main supply voltage. Larger power losses are due mainly to the C_{SERIES} capacitor(s). Larger capacitors can be used to reduce losses, but they require an adequate ripple-current rating. If substantial power is required from boost voltage rails, you should still consider a separate transformer or additional windings. **EDN**

Standalone digital voltmeter uses a multichannel ADC

Branislav Korenko and Marek Černý, Slovak University of Technology, Bratislava, Slovakia

This Design Idea was realized for voltage/current measurement on a four-channel analog voltage source but has wide use in many other applications. The design is based on the Atmel ATmega8-16AC microcontroller and the Maxim MAX1230 12-bit ADC (**references 1** and **2**). Although the microcontroller has an internal 10-bit ADC, it's more efficient to use an external multichannel ADC than to multiplex more analog channels to the ATmega8-16AC differential ADC inputs.

You accomplish the communication between IC_1 and IC_2 via the SPI according to the instructions in **Reference 2**. R_{17} and R_{18} are pull-ups for the end-of-conversion flag and chip-select modes. Signals for the SPI communication are tapped at header P_4 for a programmer connection. Pushbutton S_2 connects the IC_2 reset pin to ground; R_{22} and C_{42} debounce IC_2. Similarly, R_{19} and C_{39} debounce the auxiliary S_1 button connected to the INT0 pin of IC_2, which is used to switch between resolution patterns on the display.

IT'S MORE EFFICIENT TO USE AN EXTERNAL MULTICHANNEL ADC THAN TO MULTIPLEX MORE CHANNELS TO THE MICROCONTROLLER'S DIFFERENTIAL ADC INPUTS.

IC_2 pins 23 to 28 are used through P_2 for communication with the 20×2-character BC2002CBNHEH$ LCD Bolymin display (**Reference 3**). Trimpot R_{21} sets the display contrast. You can use IC_2 outputs RXD and TXD for USB communication via an optional USB-to-UART interface, such as the FTD232BM (not shown in **Figure 1**), for the purposes of data logging.

IC_1 analog inputs AIN0 to AIN15 are connected to eight voltage dividers R_1 to R_{16}. The divide ratios depend on the maximum input voltage to be measured. Also, you should take into account the reference voltage on pin REF+ to use the full bit resolution of the ADC. The IC_1 analog inputs work in track-and-hold mode, so input impedance can affect the conversion acquisition time. As a result, input capacitors C_1, C_2, and C_3, with values

according to **Reference 2**, are used for differential inputs AIN0 and AIN1 on IC_1, and the same input capacitor arrangement is repeated for the other analog inputs. IC_1 has a sampling rate up to 300k samples/sec, so you can digitize low-speed transient events and measure periodic signals with bandwidths exceeding the ADC's sampling rate by using undersampling techniques. Also, antialias prefiltering of the input signals is necessary.

Shunt regulator IC_5 generates the external 1.25V REF+ for IC_1 using R_{24} and R_{23} to set the appropriate current consumption according to **Reference 4**.

Select power transformer TR1 for your local ac voltage (the schematic shows 230V ac with a 0.25A fuse) and fuse appropriately; that is, 0.5A when used at 120 V ac. The transformed voltages are rectified with diode bridges D_1 and D_2 and stabilized with 7805 series regulators. One 5V branch is used directly to supply the multichannel voltmeter; the other is auxiliary for global use.

Code listings for IC_2 are available with the online version of this Design Idea at www.edn.com/4400220. This work was supported by the Slovak Research and Development Agency under contract No. APVV-0062-11. EDN

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2 "MAX1226, MAX1228, MAX1230: 12-Bit 300ksps ADCs with FIFO, Temp Sensor, Internal Reference," Maxim Integrated Products Inc, December 2010, http://bit.ly/RSKccx.

3 "LCD display, 2x20 characters, 5x7 dot matrix," http://bit.ly/Sg8AHt and http://bit.ly/TQHO5A.

4 "LM4041 precision micropower shunt voltage reference," Texas Instruments, February 2006, http://bit.ly/RSSP6T.

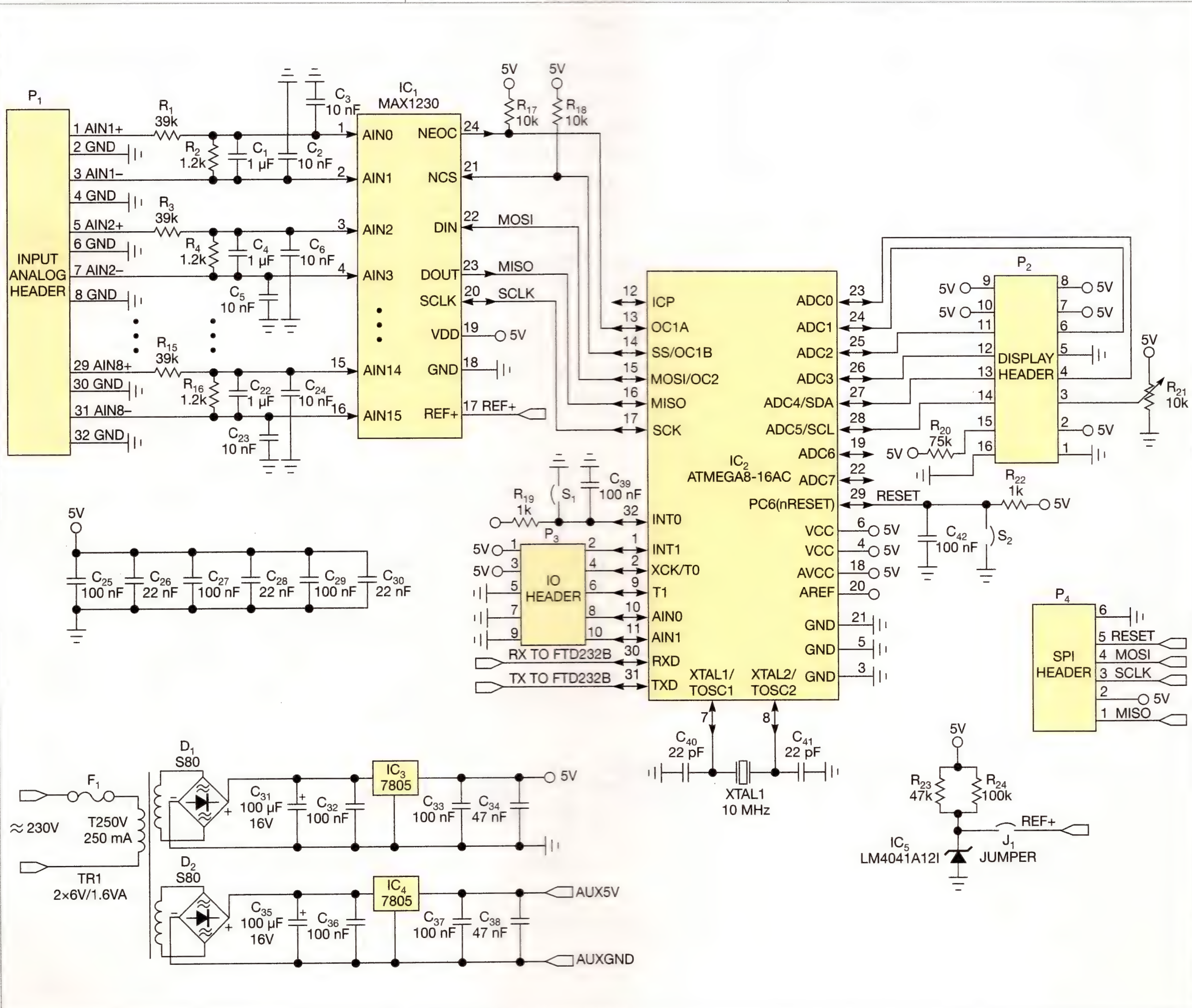


Figure 1 You can use a multiple-channel ADC, along with a microcontroller and LCD display, to make this low-power, multichannel voltmeter.

Originally published in the August 19, 1981, issue of *EDN*

1-IC design monitors ajar doors

Fred Hicks, General Electric Co, Louisville, KY

If someone in your family has the habit of not completely closing a drawer—or perhaps the food freezer's door—you'll appreciate this design. It senses an ajar door and, if the situation isn't corrected within 20 sec, sounds a beeping alarm.

The circuit, shown in **Figure 1**, is controlled by a magnetic reed switch that mounts within the cabinet (food freezer in this case) and the magnet on the door. So long as the door remains closed, the switch is closed and the alarm is disarmed.

Opening the door in turn opens the switch, and C_1 starts charging up through R_1. Approximately 20 sec later—the delay allows for authorized usage—the voltage at pin 9 is high enough to turn on the oscillator formed from C, D, R_2, R_3, and C_2. This oscillator, operating at approximately 1 Hz and a 50% duty cycle, in turn pulses the piezoelectric transducer's 3-kHz oscillator.

Closing the door allows C_1 to discharge through R_6, an action that disables the low-frequency oscillator and, therefore, the transducer's oscillator. You can override the alarm via S_1 when the door must remain open.

Editor's Note: You might want to consider using other values for R_1 and C_1. The values shown for R_1 and R_6 result in a continuous 27-μA battery load when the door switch is closed. This drain is approximately 10 times greater than what the rest of the circuit consumes in standby. Changing R_1 to, say, 66 MΩ (3×22 MΩ) and C_1 to a 1-μF Mylar capacitor preserves the 20-sec delay and reduces the resistor's loading to approximately 0.1 μA. Additionally, by using the 1-μF Mylar unit rather than a 60-μF capacitor, you considerably reduce the possibility of the 60-μF device's leakage current adversely affecting the timing. EDN

IF YOU DON'T CLOSE A DOOR THAT'S POLICED BY THIS CIRCUIT, YOU'LL HEAR ABOUT IT 20 SEC LATER. YOU CAN OVERRIDE THE ALARM WHEN THE DOOR MUST REMAIN OPEN.

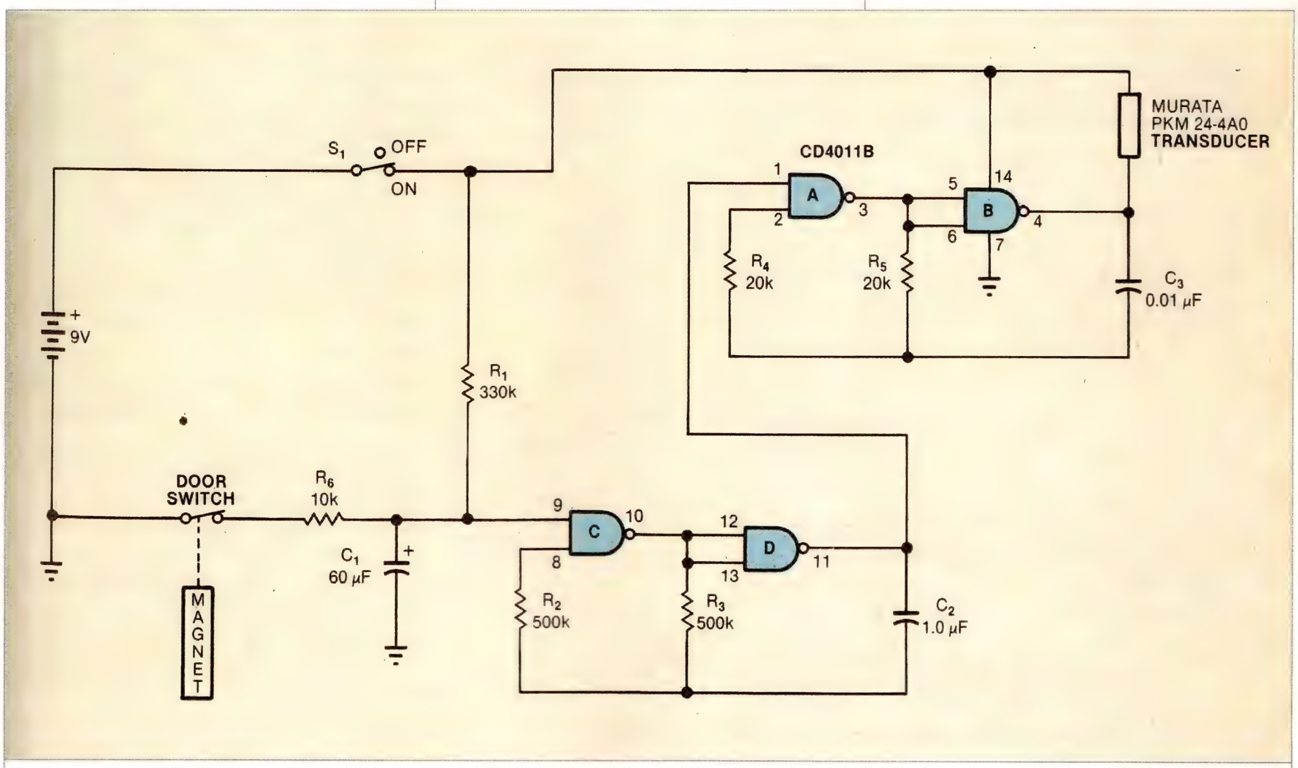


Figure 1 If the door and its switch are open, the low-frequency oscillator (C and D) pulses the transducer's 3-kHz driver ON and OFF.

Recovering lost profits through reverse logistics

The high-tech industry faces two divergent challenges in product-life-cycle management. Consumer electronics are being upgraded and replaced more quickly than ever. In 2009, according to management consulting firm McKinsey & Co, mobile-phone makers introduced 900 more varieties of handsets than they did in 2000. And high-end, high-value electronics equipment is being designed, and used, for the long haul. These dynamics put the electronics supply chain in a unique position to provide an expanded array of services to the high-tech ecosystem.

Consumer goods that are set aside due to an upgrade can be returned, refurbished, and redeployed, thereby retaining their value for the manufacturer. Heavy equipment that is otherwise operating efficiently often requires fast and dependable post-sales repair and support. Increasingly, electronics OEMs are relying on reverse-logistics services to manage these complex transactions.

"Many manufacturers view return and repair activities as a cost center," says Scott Hertel, head of the North American high-tech customer solutions team for UPS Logistics and Distribution. In reality, experts say, a solid reverse-logistics program can help companies increase revenue by up to 5% of total sales.

Moreover, electronics OEMs aren't responsible just for developing new products. They now have to manage these products from cradle to grave. Electronic goods are in the crosshairs of environmental mandates such as the European Union's ROHS and WEEE (Waste Electrical and Electronic Equipment). OEMs, not their subcontractors, are responsible for compliance with such directives.

This situation has become a significant challenge for manufacturers of high-value equipment. Ken Stanvick, an environmental consultant, explains that high-end medical equipment has an expected lifespan of 15 to 20 years. Under the European Union's ROHS recast, medical OEMs will soon face a quandary. Beginning in 2019, medical equipment sold from the European Union to secondary markets will have to comply with the European Union's most recent environmental standards. It is likely the components used in much of this equipment will be out of compliance or obsolete by 2019, Stanvick adds. "Sourcing these components and bringing this equipment up to spec is going to be a nightmare."

Due in large part to outsourcing, electronics OEMs are no longer well prepared to handle returns, repairs, refurbishment, and redeployment of many electronics products. Logistics providers handle most of the administrative tasks of identifying, shipping, tracking, and managing product sales and returns. A variety of companies, from retail outlets to full-fledged repair depots, provide technical services and product support.

"Companies are finding it hard to integrate these functions into a single service model," UPS's Hertel says. "In 2010, we had an opportunity with an OEM in Europe that wanted to combine the process of logistics with technology support. That brought us to Jabil [Circuit Inc], and what started as an alliance has evolved into a more formal structure between the organizations."

Hertel and Chuck Henry, senior director of business development at Jabil, recently participated in a Webinar focused on reverse logistics. View the archived presentation at http://bit.ly/T36eMH.

—by Barbara Jorgensen, *EBN* Community Editor

This story was originally posted by EBN: *http://bit.ly/V9WePm.*

GREEN UPDATE

GREEN TECH INVESTMENTS CONTINUE TO RISE

According to the Worldwatch Institute, an independent research organization, India's investment in solar and wind power increased by 62% in 2011 from 2010 levels—the highest growth rate for any single country. Although total investments from developing countries—identified as China, India, and Brazil—lagged behind those of industrial nations, the sum reached \$89 billion last year. Total new investments in renewable power and fuels reached \$257 billion in 2011, with industrial nations accounting for \$168 billion overall, the Institute reports.

The United States and China are striving to become leaders in alternative-energy technology and are embroiled in a trade battle over solar cells and panels. China continues to invest heavily in alternative energy, with \$52.2 billion spent in new investments in 2011—the highest for any single country. In terms of the pace of growth, however, the United States scored a 57% increase over 2010 levels, with \$50.8 billion in new investment.

Solar continues to be the leading contender in renewable energy and a key market for high tech. That correlates to a downside for manufacturers of solar cells and related equipment, however, which are dropping prices to remain competitive. **—by Barbara Jorgensen**

This story was originally posted by EBN: *http://bit.ly/T1J8I7.*

productroundup

CONNECTORS

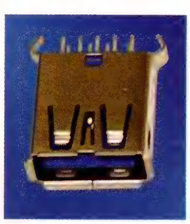
Harting har-flex variants offer 1.27-mm contact pitch

Harting has added variants to the robust har-flex PCB connector family to extend the family's versatility for board-to-board and board-to-cable applications with a contact pitch of 1.27 mm. Harting applies a special follow-up treatment in the punching process to ensure a smooth contact point between male and female contacts, minimizing wear and ensuring vibration resistance. The har-flex insulation displacement connector for flat-ribbon cable provides a secure catch that prevents unintentional removal of the cable from the circuit board. A tensile relief clamp is available as an option to protect the cable insulation-displacement connection from impact. Harting also offers prefabricated cables to customized designs. The different har-flex variants can be freely combined to enable modular device configurations. The variable number of contacts, from six to 100, optimizes spatial requirements on the circuit board. Har-flex data-transmission specs meet the requirements of modern transmission protocols, such as Gigabit Ethernet and PCI Express.

Harting, www.harting.co.uk

FCI USB 3.0 connector handles 5-Gbit/sec data

The SuperSpeed USB 3.0 connector supports a 5-Gbit/sec data rate and a faster sync time to provide a tenfold performance increase over USB 2.0 connectors. FCI optimized the SuperSpeed USB 3.0 connector for power efficiency and provided the bandwidth and headroom required for emerging consumer and industrial data applications.



The connector allows for up to 3500 mating cycles and features added pins to handle faster USB signals and to support wave-soldering applications. The USB 3.0 connectors are colored blue on the interior to distinguish them from USB 2.0 connectors. Mouser quotes a price of just under 47 cents (5000) and a six-week lead time for a USB 3.0 receptacle type A R/A, 9P with gold flashing. Pricing for a USB 3.0 receptacle type A vertical, 9P, 30U is roughly 63 cents (5000), with a factory lead time of nine weeks.

FCI, www.fci.com

Bulgin push-pull coupling Buccaneers have waterproof seal

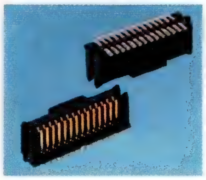
The waterproof power, signal, and data connectors in Bulgin's Buccaneer 6000 series combine a push-pull latching mechanism with a 30° twist lock to connect up to 10 times faster than a traditional screw-thread mechanism. This latest addition to the Buccaneer lineup meets IP66, IP68, and IP69K standards; comprises data (USB or Ethernet), signal, and power versions up to 16A, 277V; and complements the screw-thread Buccaneer range. Available in fully interchangeable metal and plastic constructions, the body moldings and pin carriers create a robust interface while avoiding damage during coupling, according to the company.

Bulgin, bulgin.co.uk

ERNI mezzanine MicroStac aids design flexibility

The MicroStac mezzanine connector combines the male and female connector halves into one solution to reduce inventory cost. The connectors, available in a 5-mm stack height, offer two points of contact and handle up to 1.6A/contact to ensure reli-

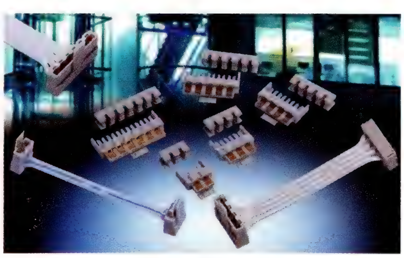
ability in applications involving high shock and vibration. The connector design offers mismating tolerance of up to 0.7 mm of side-to-side "float" and ±4° of angular misalignment between the connector halves and their respective PCBs. The contact design provides up to 1.5 mm of wipe length for use in applications requiring up to 6-mm stack height. MicroStac connectors are available in 6, 10, 12, 14, 50, and 54 positions. Typical unit pricing starts at 93 cents for a six-position connector; lead time is eight weeks.



ERNI Electronics, www.erni.com

Wire-to-board IDCs for industrial, lighting apps expand AVX's 9159 series

Wire-to-board plug and socket IDCs (insulation-displacement connectors) from AVX Corp expand the company's 9159 series of SMT connectors to facilitate the cost-effective termination of 22-24AWG discrete or cabled power and signal wires into standard 9159 series two-piece connector systems. The miniature connectors carry up to 5A per contact (125V ac, 10 cycles), can function at up to 125°C for extended periods, and enable co-planar PCB mating for use in applications ranging from office lighting and medical devices to harsh transportation environments. Wire assembly support blocks enable the single-step termination of two through six wires with any standard benchtop press. Gold-plated beryllium copper contacts ensure reliability in harsh environments. Daisy-chain and wire-stop termination options are available.



AVX, www.avx.com

Cliff airtight connectors target active-loudspeaker apps

Cliff Electronics says its airtight XLR sockets and Cliffcon 1/4-in. JumboJack plugs solve long-standing problems for professional-grade-audio manufacturers and live-music producers. Cliff developed its airtight XLR sockets for the active loudspeakers that are common in studio monitoring and similar high-fidelity audio applications. Air leakage from conventional connectors is an acoustic problem in high-quality loudspeaker design, particularly the "infinite baffle" types often found in recording studio and broadcast applications. The connectors are inherently gas-tight and have a sealing gasket between the flange and the mounting panel. The Cliffcon JumboJack plugs, available with straight or right-angled body shells, can accept cable diameters of up to 15 mm while still allowing those large-diameter cables to be connected to conventional 1/4-in.-jack plug contacts. Connection is via screw-type cable clamps. An integral cable strain-relief grommet can be adapted to suit the cable diameter being used.

Cliff Electronics, www.cliffuk.co.uk

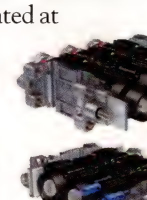
Amphenol deploys Micro-USB Terrapin for military mobiles

Amphenol Corp designed its Micro-USB Terrapin connector series to hold up in harsh operating environments for use by military personnel. The design pairs the ruggedness of an IP68 sealed connector with Micro-USB to support USB OTG (On-The-Go), letting portable devices communicate directly with each other without the need for a host computer. The shell design of the Terrapin series ensures blind mating and maintains IP68 sealing in both mated and unmated conditions. Available in various ROHS-compliant plating finishes, the connectors are suitable for industrial as well as military applications, offering high-performance grounding and EMI screening. The use of brass instead of aluminum provides an increased number of mating cycles (2000). The series offers five keying options within a miniature-footprint diameter of 16 mm.

Amphenol, www.amphenol.co.uk

Multi-Contact MPC power-link modular plug rides rails

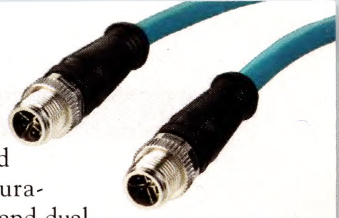
Multi-Contact AG designed its MPC modular plug connector for power transmission in electric-rail vehicles, but the modular design suits a range of applications. Rated at 3600V and up to 700A, the units can be used for connecting transformers, traction motors, inverters, and batteries as well as intercarriage power links. The MPC can combine up to 15 single-pole power contacts, with up to five joined side by side in up to three layers. Versatility is enhanced by the availability of linear and right-angled connectors, making the units highly compact. A range of compatible insulators



is available for various contact diameters; cable cross-sections from 10 to 240 mm^2 are accepted. The connectors are rated at IP67 when mated and provide more than 500 mating cycles. They are vibration and shock tested in accordance with DIN EN 61373.
Multi-Contact, www.multi-contact.com

Molex touts signal integrity to 10 Gbits/sec for M12 Cat 6A system

Molex Inc designed the Brad Micro-Change M12 Cat 6A connector system for vision systems and other high-speed data-transfer applications in harsh environments. Conforming to TIA and ISO/IEC Cat 6A specifications for high-speed Ethernet signal integrity up to 10 Gbits/sec, the high-pin-density connector system features an x-coding cross-shielding design, conforming to IEC 61076-2-109, for transmission reliability in frequency bandwidths up to 500 MHz. When mated, the shielding crosses of the connector and receptacle overlap to achieve optimal signal performance without system noise interference. Available in two- through five-, eight-, and 12-pole configurations; in single- and dual-keyway designs; and with straight or 90° plugs, the connectors are suitable for Class 2 applications.
Molex, www.molex.com



EDN ADVERTISER INDEX

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 BILL FURCH • FUTUREPLUS SYSTEMS CORP

A probe without a paper trail

Back when I was working for a major test-equipment manufacturer, another engineer and I were asked to design and assemble a remotely controlled test system for data-acquisition probes. The system contained signal sources, voltmeters, frequency counters, and other test equipment that could communicate over IEEE-488 (HP-IB).

The controller was one of the first desktop computers, with the program stored on a cassette tape and written in BASIC. We had 8k of memory for storing the program, which was compiled, or "interpreted," each time it was run. With no memory space to spare, we didn't spend much time commenting our code.

The system ran a series of electrical tests automatically on each data-acquisition probe as it came off the assembly line. The operator—a skilled assembly worker rather than a fully trained technician—would plug the probe under test into the test system, initiate the program, and then simply watch as the program caused the signal and voltage sources to be applied to the probe, monitoring the results acquired by the voltmeters, frequency counters, and so on.

When the desktop monitor indicated that a probe under test had passed, the operator would box up the probe and send it to final packaging and then into stock. When a probe failed, the desktop computer printed out a short message indicating which test had failed and what the failure parameters were. The operator would tear off the failure report from the printer (a thermal model with a paper roll), staple the message to the probe, and hand off the unit to a senior technician for debug and repair.

We tested thousands of probes on this system, finding and fixing problems as they arose, until we began to think we had troubleshot every possible problem. One day, though, the operator said she was having a problem getting some of the probes to complete the tests; the program would get to a certain point and then "hang." I went out to the manufacturing line and verified the problem. Because we were running so many tests automatically, it was difficult to test one of the probes manually. I pored over the program—which, you'll recall, didn't have a lot of comments—trying to remember what each section did.

After a couple of hours, I approached the engineer who had co-designed the system for a fresh perspective. He came out to the manufacturing line, and we both sweated for a couple more hours. The manufacturing manager came by a few times and glared at us for having shut down his test line. It was a Friday afternoon, and neither of us looked forward to coming in on a Saturday.

Suddenly, the other engineer looked at the desktop printer and said, "What does that amber light mean?"

The printer had two LEDs—one green, for power on, and another, unlabeled indicator that I had not noticed or cared about until now. My colleague reached over and opened the paper-access door, revealing a cardboard tube that had once held paper.

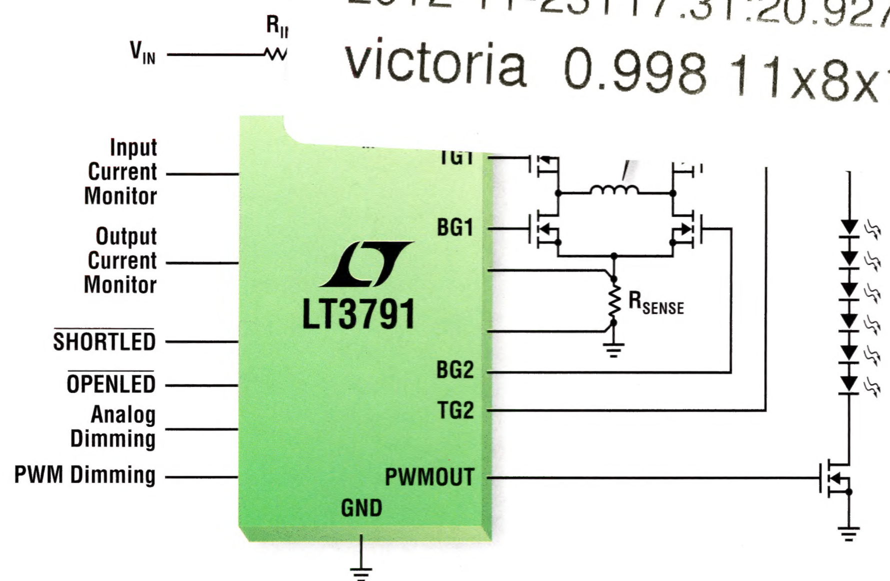
We had found our "intermittent" problem: When a probe under test passed, the computer didn't need to print a failure report; when a probe failed, the computer would try to print out the failure data but couldn't. The printer would send the computer an interrupt reporting that it was out of paper, but we had failed to include the scan for that interrupt in the program.

We looked at each other. We had designed a sophisticated automated test system and had used it to test thousands of probes successfully. But we hadn't accounted for the simple inevitability of the printer running out of paper.

We revisited the program and found a bit of memory space to accommodate the "out of paper" interrupt. Then we told the manufacturing manager we had his test line back up, and we went home that afternoon looking forward to a peaceful weekend away from the office. EDN

Bill Furch is vice president of marketing and sales at FuturePlus Systems Corp. He holds a bachelor of science degree in electrical engineering from the University of Denver.

100W-
Buck-B



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